Advanced Computational Capabilities for Exploration in Heliophysical Science (ACCEHS) --- a Virtual Space Mission

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Executive Summary

In the dynamically complex, nonlinearly coupled domains of heliophysics, the efficient use of computers is as important as access to state-of-the-art *in situ* and remote-sensing instrumentation. Computers help us explore where we cannot sense, build a comprehensive view of very sparsely sampled environments, provide forward modeling where inversions fail, and put the heliophysical domain into a controllable laboratory setting. Computers are also are critical in processing the terabytes of data coming from both real-world and virtual-world experiments.

With the development of computer hardware supported by large economic interests in industry, we can leverage these investments with a fraction of their true cost to rapidly move beyond the decades-old legacy codes we now mostly work with, improve the foundations and capabilities of the underlying physical models, integrate across physical domains, and reach out across wide ranges in scales. This is societally relevant as we work towards more realistic forecasting of space and terrestrial weather and climate, capitalizing on advances in computer architecture and data storage to increase the capability of our workforce.

As discussed in a community-wide workshop that is the foundation for this concept paper, multiple critical problem areas in heliophysics are ready to be moved forward through advanced computational capabilities, with benefits across multiple sub-disciplines and with value to society. Examples of such transformational projects include:

- Generation and emergence of active regions from the convective envelope of the Sun;
- The evolution of the ambient solar corona and its coupling to the inner heliosphere;
- Understanding and parameterizing the kinetic solar wind from the inner to the outer edges of the heliosphere;
- Acceleration and transport of energetic particles in the heliosphere;
- Impact of severe storms on the geospace environment;
- Accurate models of the radiation belts;
- Ionosphere-thermosphere-magnetosphere (ITM) coupling;
- Prediction of communication outages due to ionospheric density irregularities and turbulence.

Recommendation: We recommend that NASA, perhaps in partnership with NSF and other agencies, should lead by establishing a new peer-reviewed program in which critical-mass groups of heliophysicists, computational scientists, and applied mathematicians can be brought together to address transformational science questions that support its flight missions and advance heliophysics. The level of synergistic collaboration of such groups, requiring $5-10M per project spread over several years, exceeds what is currently supported within GI, TR&T, HTP, or SR&T program envelopes. This new program should eventually support up to five groups with steady funding for periods of up to five years at an approximate level of $2M per year each. These groups should primarily pursue a scientific problem, advancing through reviewed milestones to design and use tools for theory, modeling, and data assimilation that will exploit the capabilities of state-of-the-art supercomputers. In doing so, they should also support the training of postdoctoral scientists and graduate students in advanced computational capabilities.

While the concept underlying this paper has taken on special urgency in recent years, the 2003 Decadal Survey Report emphasized the important role of computation in its "Coupling Complexity Research Initiative". That Report identified some key issues that remain as valid today as they were nearly a decade ago, including: (i) the importance of clearly articulated support and funding lines for model development, (ii) the need for computer hardware, which should be treated like hardware for experimentation, (iii) the necessity of science questions driving computational initiatives, and (iv) the importance of supporting data assimilation and exploration techniques in synergy with computational model development.

1. Background

Computational modeling, simulation, and data analysis have been among the most important drivers of scientific discovery during the last three decades. This progress has been enabled by remarkable leaps in computing technologies, producing parallel computers of great power and speed which have been brought to bear on increasingly sophisticated software and efficient algorithms. It is reasonable to anticipate a near-future transition from the present-day terascale and petascale systems to the exascale, which will empower the science community further to undertake challenges that can be potentially transformational.[2]

The heliophysics science community is experiencing a rapid and radical transformation because of vast increases in the sophistication of instruments and in data volumes. Progress in our understanding of heliophysical processes requires that data analysis be combined with computational modeling, numerical simulation, and data-assimilation programs. The effectiveness of our community-wide theory, modeling, and data assimilation and analysis efforts depends critically on the development of innovative numerical algorithms and their use on high-performance computing platforms, as we see happen in other scientific disciplines (such as astrophysics, high-energy and nuclear physics, plasma and fusion science, and climate prediction and change), which are well-positioned to exploit fully the power of new computing technologies. We cannot rely on the slow diffusion of the fruits of the efforts made by other scientific and engineering disciplines, but need to actively work on advancing our discipline's capabilities to meet the demands for scientific breakthroughs, the design of next-generation space missions, and to tap into the pool of new and young talent, eager to bring the power of new computing technologies and methodologies to bear upon heliophysical science challenges.

A community-wide Workshop on Advanced Computational Capabilities for Exploration in Heliophysical Science (ACCEHS), was held on August 16-18, 2010 at NCAR in Boulder, Colorado (http://www.hao.ucar.edu/ACCEHS/). The Workshop brought together over 80 scientists in heliophysical science, as well as experts from the climate and computer science communities. In what follows, we describe the key findings of the Workshop, cast in the form required by a concept paper for the Decadal Survey, recommending possible strategies for action summarized above. A more detailed Report for the ACCEHS Workshop is currently being written.

2. Key Challenges and Opportunities in Heliophysical Science Disciplines

The concept underlying this paper touches on all three elements of the present Decadal Survey: Atmosphere-Ionosphere-Magnetosphere Interactions, Solar Wind-Magnetosphere Interactions, and Solar and Heliospheric Physics. The primary goal of this section is to articulate challenges or questions where targeted investment in advanced computational capabilities has the potential to transform heliophysical science. Our goal is *not* to assemble a comprehensive list, and certainly not to imply a prioritization. The topics identified in this Section should be viewed as examples of challenges that can take heliophysical science to the next and higher level of discovery.

2.1 Generation and emergence of active regions from the convective envelope of the Sun

Magnetic activity on the Sun originates from hydro-magnetic dynamo action in its highly turbulent convective envelope. A unified, comprehensive understanding of the diverse range of magnetic activity exhibited by the Sun, from small-scale flux elements in the photosphere to global patterns of magnetic activity such as the sunspot cycle, remains an unfulfilled challenge. In particular, understanding how sub-surface magnetic flux emerges into the solar atmosphere, energizes the corona, shapes the heliosphere, and regulates space weather is an essential prerequisite in the effort to understand solar variability and its impact on the Earth and other planets of our solar system.

Modeling the generation and emergence of magnetic flux on the scale of active regions requires a realistic physical description of the complex boundary layers that straddle the Sun's convection zone. Near the base of the convection zone, large thermal, rotational, and magnetic gradients promote the generation, accumulation, and subsequent destabilization of magnetic structures that can buoyantly rise to the photosphere. As these structures pass through the visible surface and expand into the solar corona, they traverse a thin boundary layer where the physical environment changes drastically. Plasma densities drop by ten to twelve orders of magnitude, radiation and electron thermal conduction replace convection as the primary means of energy transport, and magnetism overtakes gas pressure as the dominant energy reservoir. The physics of this transition is particularly complex in the solar chromosphere, where shifting ionization states and non-local radiative processes become energetically important. Similarly, the physics of the boundary layer at the base of the convection zone is complicated by internal and interfacial wave modes and tachocline instabilities.

The challenge, then, is to develop the theoretical and computational techniques necessary to model these physically, spatially, and temporally disparate regimes in a way that retains the essential physics well enough to interpret current and future ground and space-based observations. Currently, global convection simulations exhibit differential rotation and large-scale dynamo action but do not have sufficient spatial resolution to capture the formation and destabilization of concentrated flux structures. Local flux emergence simulations adequately capture the radiative MHD of the upper convection zone but rely on idealized initial conditions and simplified, spatially-limited models of the chromosphere and corona. A unified, higher-fidelity model is within reach but will require sophisticated, coupled, numerical algorithms that can fully exploit next-generation computational resources.

2.2 The evolution of the ambient solar corona and its coupling to the inner heliosphere

Many of the essential questions of solar physics are reflected in those about the structure of the solar corona. What mechanism(s) heat the corona? How is the fast solar wind accelerated? What is the origin of the slow solar wind? An understanding of coronal structure is not only important in its own right, but is implicit to understanding the geomagnetic effects of CMEs.

Phenomena in the solar corona and solar wind occur at many different scales. Observations of smaller scale phenomena give us clues to the fundamental processes that heat the solar corona and accelerate the solar wind. Models of the processes that drive these phenomena (e.g., reconnection, wave heating, and acceleration) are highly idealized but allow us to explore the viability of different mechanisms. Large-scale observations of the corona show us the consequences of the small-scale behavior –coronal streamers, coronal holes, the slow and fast wind. Global models of the corona and wind can capture much of this behavior, but must use empirical prescriptions or parameterizations of the smaller-scale physics to obtain realistic results – these constraints are imposed by the lack of resolution available to incorporate more basic physical ideas. These disjoint treatments make it difficult to test and improve theoretical models.

To understand which dominant physical mechanisms shape and power the solar corona and solar wind, global models must incorporate the small-scale processes as consistently as possible so that we can directly test theories with observations. Current state-of-the-art models cannot resolve the effects of random photospheric motions, which shuffle the footpoints of the coronal magnetic field and allow closed field lines in the streamer belt to interact with nearby open field lines in the coronal holes. Will significant reconnection occur? Can the resulting plasma release account for properties and extent of the slow solar wind? The introduction of these dynamics require ~10-100 times the number of grid points to resolve the subsequent scales. Breakthrough calculations (10^9 grid points and beyond) are becoming tractable as computers transition to megacore architectures. A major model development program is urgently required to take advantage of this opportunity, because present-day codes cannot be simply extended to the new state-of-the-art machines. Extensions to the physics of the models are also necessary to accomplish these groundbreaking simulations. For example, multi-fluid calculations with ionization equilibrium equations for the different species will allow the composition of the solar wind to be predicted from the models and tested against observations. Kinetic physics may very well be necessary to completely understand solar wind heating and acceleration, and may eventually need to be incorporated via coupling of kinetic simulations to MHD models.

2.3 Understanding and parameterizing the kinetic solar wind from the inner to the outer edges of the heliosphere

Although our well-developed and widely applied MHD ‘fluid’ concept of the solar wind has served us for decades as a reliable means of describing the macroscopic features of the interplanetary medium, it is inadequate to fully understand the details of the underlying behavior of the ions and electrons that make up the solar wind that the Earth is constantly exposed to. Numerical simulations of the kinetic processes involved in solar wind heating/acceleration and the wave-particle interactions that pervade the heliosphere are currently confined to local or highly simplified global treatments and cannot capture the effects of the boundary conditions and radial evolution that are so key to understanding the solar wind. Large-scale kinetic simulations of solar wind physics, accommodating more aspects of both ion and electron distribution functions in realistic coronal and interplanetary field geometries have the potential to revolutionize common working paradigms of heliophysics. For example, they can lead to improved parameterized descriptions of solar wind heating in the increasingly realistic global heliospheric simulations. They can lead to more accurate interpretation and use of ion and electron thermal anisotropies and halo electron strahl.

At the farthest edges of the heliosphere, the solar wind interacts with the local interstellar medium where the distribution of both the plasma and neutrals can be highly anisotropic and non-Maxwellian, leading to significant effects on the global heliosphere. Moreover, from observations returned by Voyager and IBEX spacecraft mapping the heliosheath and the global structure, it is clear that the structure of the magnetic field plays a crucial role in this region. These observations reinforce the need to resolve disparate physical scales and kinetic processes. An example is the behavior of the heliospheric current sheet close to the heliopause. In the heliosheath, the sector regions approach each other as the solar wind slows down. The current state-of-the-art relies on idealized models that largely neglect the complexities of the heliospheric current sheet and the intrinsic time dependence of the solar wind. The demands of modeling extremely fine scales within a 3D time-dependent MHD code over very long times, couple with the need to model the kinetic physics of neutral hydrogen and plasma processes over several solar cycles makes this one of the most challenging computational problems in space physics.

2.4 Acceleration and transport of energetic particles in the heliosphere

Understanding how solar energetic particles (SEPs) are accelerated and transported in the heliosphere is a long and outstanding problem that is at the heart of space weather and cannot be attacked without a larger effort than is currently employed. Presently, only portions of the entire problem are being addressed through separate modest numerical simulations, e.g., energy release and magnetic reconnection at the Sun, shock formation, particle acceleration by interplanetary shocks and magnetic reconnection, and particle transport through the heliosphere. Coupling these simulations, e.g., incorporating particle acceleration into a simulation of coronal mass ejection eruption, has proven to be difficult and generally beyond the currently available resources (both in terms of computational resources and in terms of funding of a team of experts for a significant amount of time).

Similar to the problem of understanding the solar wind in the heliosphere, the acceleration of SEPs requires incorporating kinetic physics and a large range of physical scales into numerical simulations. A prime example is the question of how thermal, or very low-energy particles, that move slowly with respect to the shock are accelerated by the shock to high energies, is largely ignored in current modeling. This problem involves scales that range from the gyroradius of the thermal particles (~100 km at 1 AU) to the scattering mean-free path of the highest energy particles (~> 1 AU for ~GeV protons at 1 AU). The kinetic physics is important because the shocks that accelerate the particles move slowly enough that they are affected by the microstructure within the shock layer. Current models either ignore the shock microstructure and consider the acceleration to the highest energies only, or include the microstructure but are limited in the size of the model and therefore are limited in terms of the maximum energy achieved.

2.5 Impact of severe storms on the geospace environment

The magnetosphere represents the furthest extent of Earth's environment into the surrounding plasma and electromagnetic fields of interplanetary space. It stands between the solar wind and the ionosphere-atmosphere system and thereby controls the flow of mass, momentum, and energy. The magnetosphere spans a huge volume that is highly under-sampled, due to the small number of satellites making in-situ measurements and limited remote sensing opportunities. Understanding the magnetosphere is further complicated by the dominance of coupled, nonlinear physical processes that cover orders of magnitude in temporal and spatial scales. Conditions in the magnetosphere can change in a matter of minutes from quiet-time to storm-time, and storms can last from hours to days. Large geomagnetic storms can cause serious damage to technological systems like satellites, increase the radiation exposure of astronauts, and disrupt communication and power systems. Predicting geomagnetic storms (especially severe storms) is one of the biggest challenges in magnetospheric physics.

Given the complex and multi-scale nature of the magnetosphere and its coupling to the solar wind and the ionosphere-atmosphere system, understanding its dynamics requires state-of-the-art models, computational facilities, and access to comprehensive data sets. The two most promising approaches to understanding the global behavior of the magnetosphere are MHD/multi-fluid and hybrid simulations. MHD simulations have been in use for more than 3 decades and advances in hardware and software technology have resulted in their ongoing improvement. These models, however cannot accurately describe the inner magnetosphere because they do not include the energy-dependent drifts of the pressure bearing ring current particles. Robust coupling of MHD models with kinetic ring current models is difficult to achieve at present due to the required higher temporal and spatial resolution. Hybrid models treat the ions kinetically and allow coupling of microscopic and macroscopic processes, but due to their considerably larger computational expense, hybrid simulations currently utilize a system size that is smaller than the magnetosphere. Both MHD/multifluid and hybrid models need to include ionospheric ion outflow models that will allow coupling between the magnetosphere and the ionosphere under different solar wind driving conditions. Advances in hardware technology and supporting computational libraries will allow future development of near-real-time predictive capabilities for geomagnetic storms.

2.6 Accurate models of the radiation belts

The dynamic variability of radiation belt electrons over orders of magnitude poses a challenge to modelers and a threat to our increased dependence on satellite systems vulnerable to these changes. A thorough understanding of the mechanisms involved in their access, transport, trapping, acceleration, and loss can be achieved only with a system level approach, including coupling between adjacent regions. Trapped MeV electron flux is highly variable, peaking during the declining phase from solar maximum, with strong enhancements around the ~ 11 year maximum in sunspot number. The low energy (eV) plasmasphere population which co-rotates with the Earth is continuously refilled by the topside ionosphere and stripped away by changing magnetospheric convection, typically around L ~ 4. Our understanding of the coupling of the solar wind drivers to the dynamics of the low energy plasmasphere population, and its effects on MeV electron fluxes, requires advanced modeling of wave-particle interactions near the plasmapause, responsible for determining the depth of penetration of MeV electron fluxes into the altitude range of, for example, GPS spacecraft. Recent observations of coherent large amplitude whistler waves in this region responsible for electron loss and local acceleration have been limited by time resolution of earlier measurements. Advances in spacecraft data acquisition at higher time resolution present a data storage and processing challenge similar to that faced by modelers.

Local micro-scale processes such as the generation of plasma waves and their effect on particle dynamics must be included in global models. Major computational challenges are thus to develop models that couple self-consistently the plasma and the fields across various regions of the magnetosphere, and that include both large-scale and micro-scale physics. This could be achieved by coupling global MHD and/or multi-fluid models with kinetic or full particle models, which each address different regions or physical processes. Including ionospheric outflow as well as solar wind entry in such models is essential, as such outflow/inflow repopulates the plasmasheet, the source of both energetic electron and ion components. Inclusion of plasmasphere dynamics in global models is essential, as the plasmapause has been shown to be a significant boundary affecting both radial transport and localized heating and loss of radiation belt electrons and ring current ions. Thus, particle energies span approximately six orders of magnitude over which particle dynamics must be modeled in a combined fluid and particle approach. Cross-coupling of particle populations over such a broad energy range, combined with the physical scale of the coupled system and range of timescales between global processes and localized acceleration and pitch angle scattering present major computational challenges. The development of data assimilation models will allow the integration of ground-based and space-borne data sets with models, soon to be augmented by the first spacecraft mission, RBSP, dedicated to radiation belt studies in two solar cycles.

2.7 Ionosphere-thermosphere-magnetosphere (ITM) coupling

It has become increasingly clear over the past several years that coupling processes between the lower atmosphere, thermosphere, ionosphere, and magnetosphere have a much larger impact on microscale to mesoscale behavior than previously understood. The major computational challenges are to develop accurate and robust numerical models for each region, and to seamlessly couple these models into a single, self-consistent unified model. The development of whole atmosphere models in recent years reflects these needs. Other examples include frameworks that link together models of the magnetosphere, ionospheric electrodynamics, and upper atmosphere.

An example of neutral atmospheric dynamics on the behavior of the ionosphere is the phenomenon of sudden stratospheric warming. During these events, lower atmospheric waves, such as planetary, tidal, and gravity waves, undergo significant variation and produce changes in the stratosphere, mesosphere, and thermosphere that significantly impact the electrodynamics of the ionosphere. Current modeling capabilities are inadequate to fully explain and predict these behaviors, in many cases due to the need for expanded resolution and improved boundary dynamics. Increased resolution and improved physics is critical to correctly quantify large scale waves (i.e., tides and planetary waves) and to resolve mesoscale waves (e.g., gravity waves). These waves have important implications for ionospheric variability and space weather, but not reproducible by current global models.

2.8 Predict navigation and communication outages due to ionospheric density irregularities and turbulence

A classic example of this challenge is equatorial spread F (ESF), during which the equatorial ionosphere becomes Rayleigh-Taylor unstable: large (tens of km) electron density bubbles develop and rise to high altitudes (1000 km or greater at times). Attendant with these large-scale bubbles is a spectrum of density irregularities that can extend to wavelengths as short as 10 cm. Understanding and modeling ESF is important because of its impact on space weather: the associated electron density irregularities can cause radio wave scintillation that degrades communication and navigation systems.

The first major computational problem is to seamlessly couple different spatially overlapping, physics models. Large-scale (hundreds of m) ionospheric processes are well described by fluid theory. However, a kinetic description of the plasma is needed to model small-scale wave structures (~100 m) and the turbulent cascade of energy down to tens of cm. The computational algorithms to allow self-consistent coupling of fluid and kinetic models, which need to be developed, are crucial to describe the onset and decay of scintillation-causing irregularities. The second major computational problem is modeling the electrodynamics of the IT system. All global models of the IT system assume that the geomagnetic field lines are equipotentials; this reduces the potential equation to two dimensions. To accurately describe the self-consistent coupling of large scale to small- scale density irregularities, it is necessary to have a fully electrodynamics model. This requires the development of a fully three-dimensional solver that is robust, efficient, and uses parallel processing on a non-uniform grid. The third major computational problem is to couple computational models over a large range of spatial and temporal scales. The nominal spatial grid scales for current IT system models are 2.5-5.0 degrees in latitude and longitude (i.e., 300-500 km) and 2-10s km in altitude. The nominal time scale ranges from ~10s to ~10 min. To capture scintillation-producing ionospheric irregularities in a computational model, the grid resolution has to be reduced to ~1 m, which is about three orders of magnitude smaller than is currently feasible.

3. Computational Needs and Opportunities

Progress on some of the most exciting scientific challenges in heliophysics is awaiting the development of new computational techniques and the full utilization of petascale computing. Looking across the various sub-fields, the basic requirements for new tools and approaches share many common themes. Researchers seek to understand systems with vast disparities in spatial and temporal scales. This requires accurate models governing the large-scale evolution, which may depend on a kinetic processes. New petascale machines and other advanced hardware such as general-purpose graphical processing units (GPU) offer the potential for tremendous progress on these multi-scale problems. The ability to fully exploit these computers will permit calculations (100-1000) times larger than previous efforts. However, the spatial and temporal scale separations are so large that simply adapting existing algorithms to the new hardware is not sufficient. New breakthroughs will also require improvements in multi-scale algorithms and adapting the modern advancements in algorithms. In addition, new approaches are needed to deal with the large quantity of data generated by both simulations and observations. We have identified four basic categories of computational tools to address these needs:

3.1 High performance solvers and advanced algorithms for fluid simulations

Fluid simulations play a critical role in all sub-fields of heliophysics, including neutral fluids in the atmosphere/thermosphere, electrostatic fluid models in the ionosphere, and MHD models in magnetospheric, interplanetary and solar physics. These range from 1D regional models (such as solar wind acceleration), to 2D codes (such as magnetotail reconnection models) to fully 3D global codes (such as global magnetosphere and heliosphere codes). Most of these codes were written by scientists with deep understanding of the physics but limited background in modern algorithms, and before massively parallel machines were widely available.

Efforts to develop modern fluid simulation capabilities should include three key components: improved physics and closures, advanced solvers and the ability to fully utilize existing and future computer hardware. Depending on the specific science focus, the optimum mixture may differ. For example, how to properly capture kinetic effects within fluid calculations or describe the effects of turbulence remain key issues for accurately modeling magnetic reconnection, but improvements in solver technology and/or petascale computers are also very important for performing the high-resolution simulations required to test improved fluid closures and subgrid methods. Most heliophysics simulations are physically far under-resolved, and would benefit greatly modern adaptive mesh refinement (AMR) methods and implicit time stepping. However, in order to simulate physically relevant large systems, the parallel and algorithm scalability is crucial. For explicit codes, parallel scalability is typically quite good using simple domain decomposition, and remains good for enhanced methods like block-structured AMR. While more difficult, recent work has demonstrated that implicit MHD algorithms showing such optimal algorithmic properties are possible. These issues are also important for electrostatic fluid treatments in the ionosphere, where there is a critical need for highly scalable 3D Poisson solvers on non-uniform meshes.

3.2 Advanced kinetic simulation approaches and algorithms

While fluid models have been very successful in modeling the macroscopic structure of many phenomena, there are many important science questions in heliophysics that require a kinetic description. A range of different kinetic simulation approaches have been employed including fully kinetic (ions and electrons), hybrid (fully kinetic ions and fluid electrons) as well as gyrokinetic models. Most kinetic simulations still employ a uniform mesh, with simple explicit algorithms. On the positive side, these simple well-tested algorithms can achieve excellent performance and scaling on modern computer architectures. Recent 3D fully kinetic simulation studies of magnetic reconnection have employed over ~1 trillion computational particles running on 10^5 computational cores, with an additional factor of ~10 anticipated in the next few years. These capabilities are leading to a range of new insights into the physics of reconnection, and may be extremely useful for addressing basic physics issues in shocks and turbulence. However, for many problems the spatial and temporal scale separations are so large, that simple explicit approaches (with uniform mesh) will always be limited due to rigid stability constraints and the long-time scale accuracy of the solution. While investments are clearly needed to help researchers exploit new architectures, there is an equal need for targeted investments in algorithms and multi-scale techniques. This includes, asymptotic-preserving discrete numerical formulations, non-uniform structured mesh, AMR, and implicit time stepping and/or discrete-event multi-stepping techniques. The scientific payoff will be high if researchers can effectively combine the raw power of petascale computing with modern advances in algorithms.

3.3 Computational framework: coupling physics across disparate scales

Development of a general simulation approach to handling multi-physics, multi-scale problems described by different models (codes) remains an outstanding research topic in computational physics. Problems in heliophysics will likely require software frameworks that include a superstructure layer that drives the coupled-model application, and an infrastructure layer that provides utilities and data structures for model developers. There are an abundance of heliophysics applications that will benefit from new investments in these capabilities. As one example, researchers have already successfully coupled ionosphere/thermosphere dynamics to global magnetospheric MHD codes. With petascale computers, global hybrid calculations are becoming increasingly realistic, but will still need to be coupled to ionospheric models. While hybrid calculation can properly treat the structure of ion-scale transition layers and shocks, neither approach (hybrid or MHD) can correctly capture the microphysics of magnetic reconnection. Future efforts in computational frameworks may allow researchers to couple more complete kinetic descriptions within the thin current sheets, and thus move towards a more predictive understanding of the global dynamics.

3.4 Analysis tools, parallel visualization and data mining and assimilation

Both simulations and space observations are producing increasingly larger data sets that are challenging for researchers to study with existing tools and approaches. New missions such as the Solar Dynamic Observatory have a data rate of 1.4 terabytes per day, while recent 3D kinetic simulations using the newest petascale computers are generating ~40 terabytes in a single run. Extracting new science from these enormous data sets is becoming progressively more difficult. Researchers are drowning in the over abundance of data, and legacy tools and approaches have failed to keep pace. The largest simulations are preformed at a few leadership class facilities around the country, and the resulting data sets are now far too large to move. To utilize these new machines, researchers need parallel tools to remotely visualize and manipulate the data, and to easily allow access to teams of researchers working in a collaborative fashion.

Although there have been efforts in recent years in extending simulation capabilities to petascale computers, less attention has been paid to the data analysis and visualization of the resulting large data sets.

In terms of spacecraft data, researchers have introduced data mining techniques and have worked with experimentalists in their analysis. This effort has met with considerable success and is rapidly gaining adoption. However, funding is required for further expansion of these techniques, as well as the integration of these new methods with the existing data analysis software used by experimentalists (e.g., autoplot, VO, etc.).

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2. See the "Scientific Grand Challenges Workshop Series" on extreme scale computational science, organized by the Office of Science, Department of Energy (http://extremecomputing.labworks.org/index.stm).

MMAP: A Magnetic-field mapping mission concept

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Summary

This white paper describes a novel mission concept that is designed to provide near real-time mapping of the geomagnetic field. Our idea is based on the recent discovery that a sequence of whistler-mode chorus elements measured *in situ* by a spacecraft, can be uniquely linked to a single pulsating auroral (PA) patch, observed by a ground-based all-sky imager [*Nishimura et al.*, 2010]. We propose a mission in which several spacecraft are placed in, or near, Geosynchronous Earth Orbit (GEO) suitably instrumented to measure whistler-mode chorus waves at high resolution (<1 sec). Near the average magnetic footprint of each spacecraft, we propose installing an imaging instrument that will be able to detect the pulsating auroral patch that is linked to the spacecraft, and hence uniquely tie the location in the ionosphere and magnetosphere together. The design of this mission is modular and very scalable: nominally, the imaging instrument could be an all-sky white light imager (as was the case in our example, discussed further in Sec. 3), but preferably it should include multiple wavelengths to estimate the spectral content of the precipitation. To avoid contamination by scattered light on the dayside, we suggest deploying an array of imaging riometers, placed in Antarctica in order to complement the existing array of THEMIS all-sky imagers in the northern hemisphere, and also to avoid less accessible regions in the northern hemisphere for instrument placement. The GEO spacecraft fleet could be dedicated entirely to the MMAP mission, or alternatively we could include a plasma wave instrument suite onto existing platforms that are scheduled for launch, such as the LANL or GOES satellites. The number of spacecraft-imager pairs is also scalable: we nominally recommend 6 spacecraft, distributed as uniformly as possible in Magnetic Local Time (MLT) for a spatial sampling of ~4 hours of MLT, but the mission could be as small as a single spacecraft-imager pair or it could be many more than 6. Obviously the larger the number of spacecraft-imager pairs, the better the MLT resolution we will attain in magnetic field mapping.

Relevance

The ability to observationally map the Earth's magnetic field (albeit at a single L-shell) is crucially important for many areas in space physics, including radiation belt and ring current modeling (where GEO acts as an outer boundary), plasmasheet and/or substorm studies (GEO is roughly an inner boundary), and related fields. Understanding the Earth's varying magnetic field has been mentioned directly or indirectly in nearly all guiding documents, including the 2002 NRC decadal survey (challenges 3, 4, and 5), NASA strategic plan for 2006-2016, NASA Science plan for SMD, 2007-2016, NASA heliophysics roadmap for science and technology 2009-2030, and others. This proposal includes cross-cutting science themes that are relevant to Atmosphere-Ionosphere-Magnetosphere interactions and solar wind-magnetosphere interactions, as well as the broader area of space weather and its effective prediction.

1. Introduction

The configuration of the Earth's magnetosphere is determined by the internal field of the Earth and an external current system that forms through interaction of the solar wind impinging on the Earth's main field. The complicated chain of physical processes that sets up this current system involves a coupling of the magnetosphere to the ionosphere (MI coupling), and is fundamental in many areas of magnetospheric physics. For example, knowing the magnetic field structure is essential for radiation belt and ring current particles that follow magnetic drift shells. These drift shells can change significantly and are often difficult to predict during disturbed conditions, making a comparison of fluxes in different regions unreliable and hard to compare with simulations. In spite of a large amount of observations and modeling studies of the magnetospheric magnetic field, accurate mapping of the Earth's magnetic field lines has been a problem that is as difficult to solve as it is important. This difficulty arises from the highly time-varying nature of the solar wind and magnetospheric current system, and makes it difficult to construct an accurate field model with a high precision of ~100 km in the horizontal direction at the ionospheric altitude.

In this white paper, we propose a mission based on a recently discovered method of linking a distant point in space to a point in the ionosphere. This method relies on the scattering of energetic electrons by whistler-mode chorus waves that exhibits a unique temporal pattern that can be detected and accurately located in the ionosphere using ground-based imagers. Although chorus is not always present in space (which might at first appear detrimental to our proposed mission), it is nevertheless controlled by geomagnetic activity, such that it is 'switched on' and intensifies precisely when geomagnetic activity intensifies, i.e., the magnetic field model becomes the least reliable, and when we need to know it the most! Thus, the chorus PA link is well established in moderate and active times, but additionally, it has been shown that chorus at moderate levels (10 pT to 30 pT) occurs with a surprisingly large probability (30%-40%) even in quiet times [Li et al., 2009]. In the remainder of this white paper, we illustrate the technique of linking a point in space to a point in the ionosphere, and sketch out the mission concept in Sec. 3.

2. Scientific background

The conceptual model that relates chorus emissions and PA is illustrated in Figure 1. This figure shows a group of electrons (Figure 1, blue arrows) that were initially trapped by the Earth's magnetic field encountering a chorus element propagating away from the equator (red arrows). The electrons are scattered in pitch-angle by the chorus, causing them to precipitate into the upper atmosphere, and to produce photo-emissions, that are subsequently observed by the ASI.

Figure 2 shows results for a specific event recorded on February 15, 2009. Images from the Narsarsuaq, Greenland ASI (Figure 2A) at the four selected times, display a series of PA patches with a scale size of ~100 km, at ~64°-67° magnetic latitude (MLAT) embedded in a weak background of diffuse aurora. The images in the second and fourth panels in Figure 2A were obtained simultaneously with intense lower-band chorus (Figure 2B), observed by the THEMIS-A spacecraft in the particle burst (FFP) mode, while it was located slightly to the south of the magnetic equator (ideal for detecting plasma waves). The

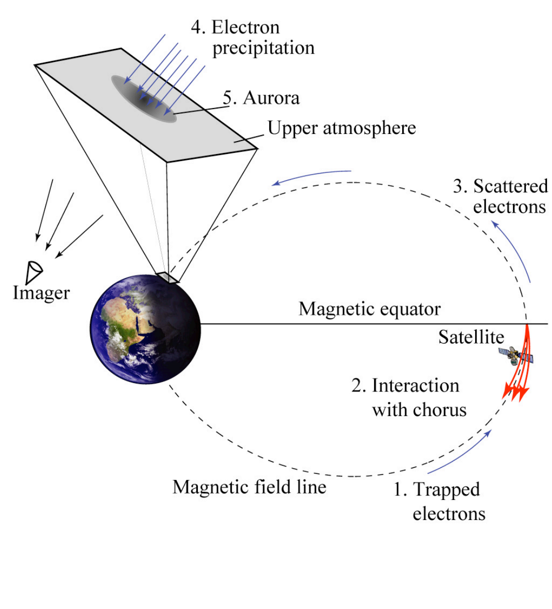

Figure 1. Schematic showing the geometry of chorus wave propagation (red arrows), electron precipitation (blue arrows) and PA.

chorus occurs as a series of repetitive discrete bursts at frequencies between 0.05 and 0.3 f_c, characteristic of lower-band emissions. Intense lower band chorus was present during this time period, while both upper band chorus (0.5-0.8 f_c) and ECH (>1.0 f_c) waves were absent, even though the spacecraft was located close to the equator.

A bright auroral patch (red arrow in Figure 2A) was identified to the west of the T96 footprint of the spacecraft, which pulsated in phase with the chorus intensity modulation, whilst adjacent auroral patches pulsated out of phase. This is the first clue of a relation between the chorus emission measured at the spacecraft and the pulsating auroral patch. The correlation between chorus intensity modulation and the PA was then investigated quantitatively by using the entire period of the wave observation shown in Figure 2B. Cross-correlation coefficients between the lower-band chorus intensity and auroral luminosity in each imager pixel were calculated to find the

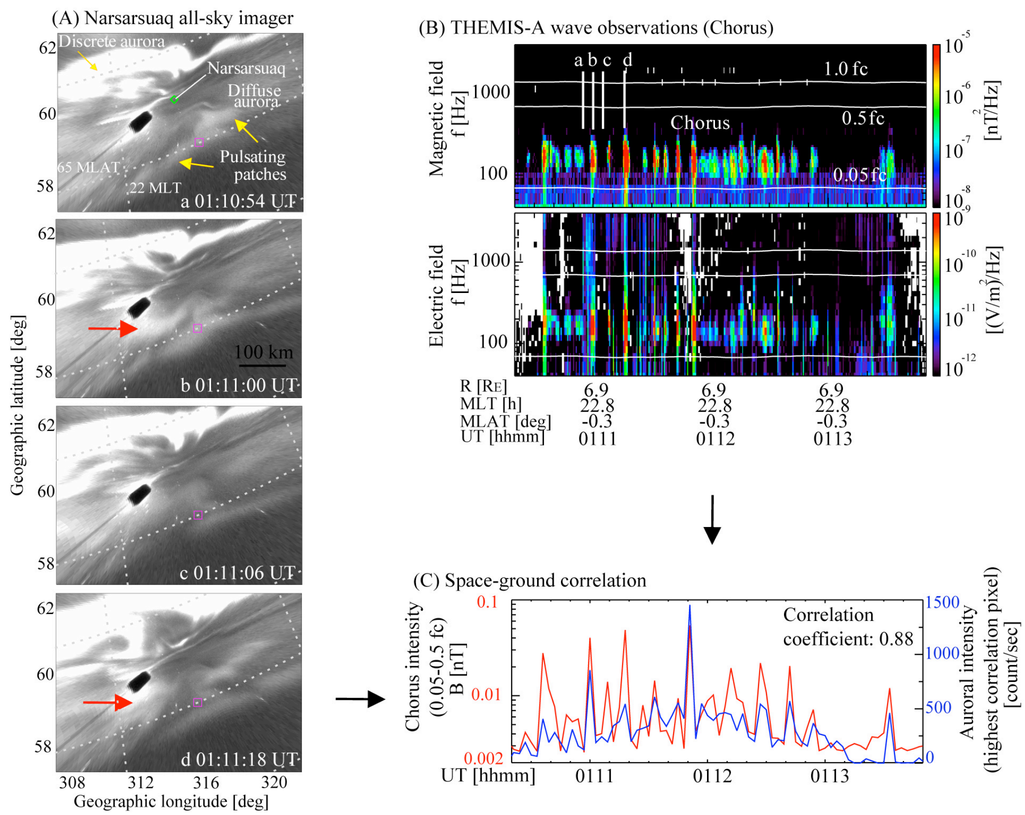

Figure 2. Coordinated observation of PA by the Narsarsuaq ASI and THEMIS-A spacecraft during 01:10:20-01:13:50 UT on 15 Feb 2009. (A) Snapshots of imager data projected onto the geographic coordinates at 110 km altitude. The pulsating patch which strongly correlates with chorus is indicated by the red arrows. ASI snapshot times are also marked in Panel (B) by white vertical lines. The pink square shows the magnetic footprint of the THEMIS-A spacecraft using the T96 magnetic field model. The center of the imager FOV is given by the green square in Panel a. Dashed lines give magnetic coordinates every 3° in latitude and 1 hour in local time. The black spot near the center of each image is an artificial object. (B) THEMIS-A observation of bursts of lower-band chorus shown in electromagnetic field spectra. The white lines indicate 0.05, 0.5 and 1.0 f_c using the measured magnetic field. (C) Correlation of lower band chorus integrated magnetic field intensity over 0.05-0.5 f_c (red) and auroral intensity (blue) at the highest cross-correlation pixel.

highest correlation pixel. Although the time lag between these two waveforms was considered, we found that the simultaneous correlation was much higher. This is consistent with the short travel times (<1 sec) of >10 keV precipitating equatorial electrons down the field line causing PA, and the short lifetime of the excited atmospheric atoms (~1 sec). Both of these timescales fall within the time resolution of the imager (3 sec). Figure 2C shows the integrated chorus intensity (red) and the auroral intensity at the pixel with the highest cross-correlation (blue). The correlation coefficient is remarkably high (0.88), and the auroral pulsations have an almost one-to-one correspondence with each burst of chorus. The high correlation supports our inference that intensity-modulated lower band chorus plays a major role in driving the PA.

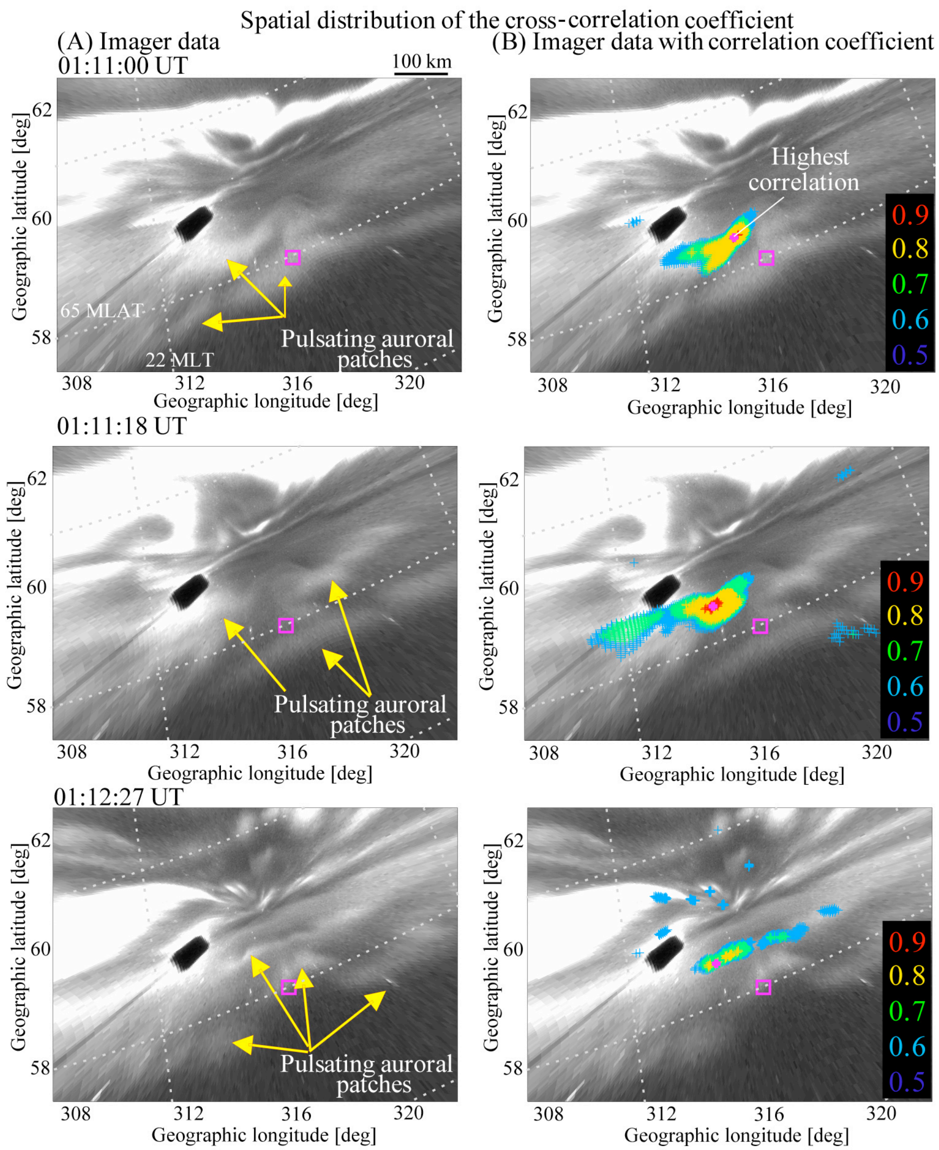

Figure 3. Temporal evolution of the spatial distribution of cross-correlation coefficients during the period of chorus observation shown in Figure 2. (A) Imager data showing PA and (B) cross-correlation coefficient superimposed onto the imager data during a 1 min time interval including each snapshot time in Panel (A). Pixels with correlation coefficient below 0.5 are not color-coded.

The spatial distribution of the cross-correlation coefficient calculated for every imager pixel is overlaid on the auroral imager data in Figure 3B. The original images are shown in Figure 3A and display pulsating auroral patches as marked by yellow arrows. The first image of Figure 3B shows a well-grouped patch of high correlation. The correlation coefficient outside this region diminishes rapidly with distance, despite several pulsating auroral patches located within the imager field of view. The high-correlation region demarcates the auroral patch marked in the second panel (b) of Figure 2A, highlighting that this is the only auroral patch that is correlated with the chorus intensity variation. The highest cross-correlation (0.91) is located 0.83˚ MLAT north and 0.07 MLT (80 km) west of the T96 prediction of the magnetic footprint.

The "high valued" (>0.5) cross-correlation coefficients calculated for the images obtained at later times (second and third rows) are spatially grouped on a pulsating patch, similar to the top row, underscoring the fact that only a single pulsating patch is stably correlated with the chorus intensity. While the patch shape slowly evolves with time, the location of highest correlation stays essentially fixed, which strongly suggests that the actual spacecraft footprint has been uniquely identified using the cross-correlation between the chorus and PA.

An important implication of the above analysis is the ability to uniquely link a point in space, to a patch in the ionosphere. Magnetic field line mapping has been a problematic issue in magnetosphere-ionosphere coupling studies, but the PA provides a unique opportunity to identify the footprint of the magnetic field line threading the spacecraft to the precision of an auroral patch (<100 km) and possibly even down to a few pixels. These results consequently provide unprecedented opportunities for magnetic field modeling, using the capabilities of wide-coverage auroral observations in conjunction with wave observations in space.

3. Mission concept

The key idea behind the MMAP mission is the establishment of Spacecraft-Imager (S-I) pairs, where the spacecraft is placed in, or near, a Geostationary Earth Orbit (GE0) and a ground-based imaging instrument is placed as close as possible to the average location of the magnetic footprint of the spacecraft, such that the S-I pair is always magnetically linked (Figure 4). In the course of a magnetic disturbance, the magnetic field configuration in the magnetosphere will change in response to the enhancement of a variety of MI current systems, and the point in the ionosphere that links the GEO spacecraft will change location, which will be observed using the technique described in Sec. 3. Through this conjugate observation, we will be able to track the time-varying ionospheric footprint of the magnetic field line threading the spacecraft. With multiple S-I pairs in different longitudes, we may determine MLT dependence of the magnetic field configuration.

3.1. Spacecraft requirements

The MMAP spacecraft will be placed in, or near GEO, such that their average magnetic footprint is always within the typical field of view of the ground-based imager. By construction an orbit that is slightly eccentric about the mean location GEO, it is possible to map over a broader range of L-shells and thus extend the range of the S-I pair. For a fleet of spacecraft, it is possible to design sub- or super-rotating orbits that do not remain fixed over a specific imager, but such that an imager always has at least one spacecraft within its field of view. Each of the spacecraft can be either dedicated missions, or simply consist of a plasma wave suite that is added onto future GEO spacecraft that are scheduled for launch, such the LANL or GOES satellites. The minimum requirement is a multi-component wave instrument (3 components of the wave B-field and at least 1 component of E-field) that can observe wave frequencies in the range of ~$0.05f_c$-3 f_c (roughly 0.1-10 kHz at GEO).

To reduce the data stream, on board processing can be employed to reduce the wave data to dynamic spectrograms, with a time resolution sufficient to resolve individual chorus elements (~0.1 sec or less). While the magnetic field configuration that we can highlight is limited to the field lines threading the GEO altitude, it has an advantage of having a continuous availability of conjunctions with ground-based instruments described in Section 3.2. Other spacecraft moving across L-shells, such as THEMIS and RBSP, will occasionally provide data for other L-shells.

3.2. Imager requirements

The ground-based imager needs to satisfy several requirements: the total field-of-view should be large enough to capture the magnetic footprint of the GEO spacecraft, even during highly disturbed periods when the footprint can deviate significantly from its average locations (roughly, FOV > 1000x1000 km). The resolution of the imager, however, should be small enough to resolve individual PA patches, or smaller (~ few km). Nominally, the imagers can be white light, all-sky imagers as was used in the example above (Section 2), but a significant improvement can be

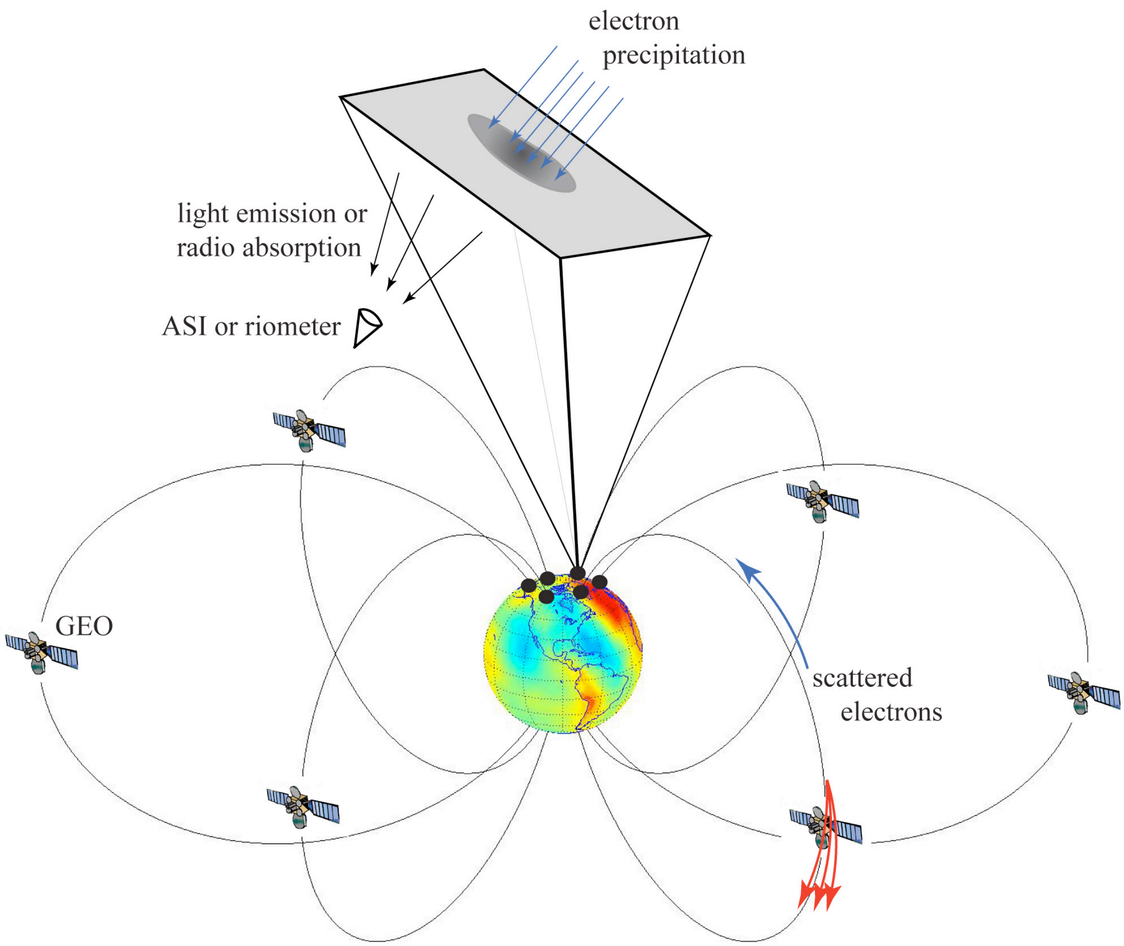

Figure 4. Schematic illustration of the MMAP mission concept: 6 GEO satellites are shown, whose magnetic footprints each thread an imaging instrument. The imaging instrument can be either an all-sky white-light (or multi-wavelength) imager, which detects light emissions, or an imaging riometer, which detects increased damping, both due to precipitating electrons.

attained in using multi-wavelength imagers, which can give an indication of the energy spectrum of the precipitated particles. Unfortunately, the imagers suffer from contamination by scattered light and are thus largely unusable on the dayside. As a remedy, we propose installing imaging riometers which are effective at all MLT, and are sensitive to the key range of energies in the PA (roughly >25 keV). We propose installing this set of riometers in Antarctica, to (i) complement the existing set of THEMIS ASI's in the northern hemisphere, (ii) to overcome the difficulties of installing scientific instruments in various regions outside of the US in the northern hemisphere, and (iii) to provide true conjugate field-mapping in the N and S hemispheres simultaneously, when possible. Although magnetic conjugate points where both northern and southern hemispheres have ground are somewhat limited, the footprint map of GEO in Figure 5 shows that Iceland to eastern Canada in the northern hemisphere have magnetic conjugacy at ~230-040 deg GLON of Antarctica. These are proposed locations to install the ground imagers.

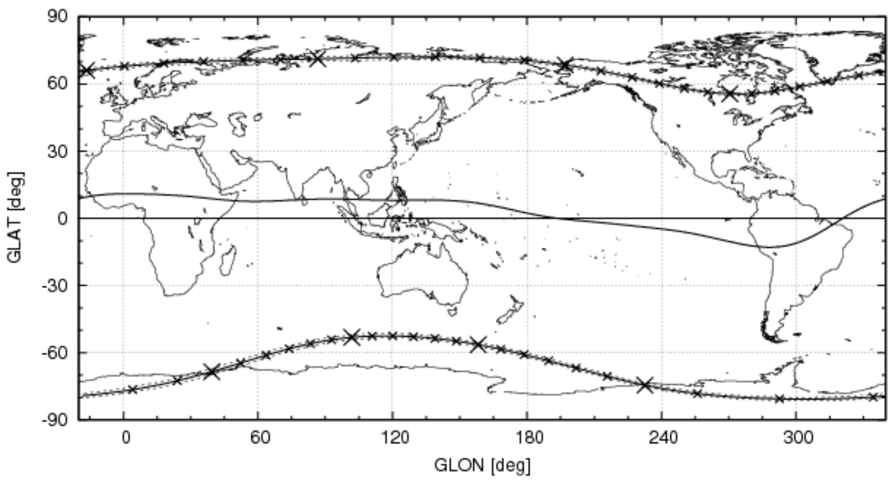

Figure 5. Geographic locations of the ionospheric footprint of the field lines threading GEO altitude (solid line). The dashed lines are for 6.1 and 7.1 RE. The small and large cross symbols show 1 and 6 MLT intervals. The Tsyganenko 01 [Tsyganenko, 2002a, b] magnetic field model under a quiet condition (IMF By=Bz=0, P_{dyn}=1 nPa and Dst=0) at 6 UT (UT is in the nightside) were used.

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The critical role of theory and modeling in the dynamic variability of the radiation belts and ring current

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Summary

The aim of this white paper is to highlight the critical role that was played by theoretical and modeling projects in the preceding decade of heliophysics research, and to urge the decadal survey committee to balance the large budgets allotted for observational missions with an appropriate level of funding for T&M. Specifically, we recommend the support of further modeling efforts dealing with wave-particle interactions in controlling the structure and dynamics of the radiation belts. We outline six key areas where substantial progress has already been made, but where further theoretical modeling is still needed.

Relevance

The Earth's radiation belts are a known hazard to satellites and astronauts in space, and thus an understanding of the key processes that drive their dynamic variability is of practical as well as scientific importance. This has been recognized and articulated in a number of documents, including:

1. NASA Strategic plan for 2006-2016, Research Objective 3B.1
2. NASA Heliophysics roadmap for science and technology 2009-2030, and NASA Science plan for SMD, 2007-2016, research focus area F2
3. The LWS Science Architecture Team report to SECAS
4. The 2002 NRC decadal survey report entitled "The sun to the Earth and beyond", challenge 3.

The radiation belts are also the focus of NASA's upcoming Radiation Belt Storm Probes mission, scheduled for launch in 2012, as well as a number of other missions including BARRELL, DSX, ORG, ORBITALS, RESONANCE, and THEMIS (as a secondary objective).

1. Introduction

In the basically collisionless plasma of the magnetosphere, the primary way that populations of electrons and ions can get transported and redistributed is through the action of plasma waves. These plasma waves lead to a violation of one or more of the particle's so-called adiabatic invariants (or constants of motion), which in turn lead to various effects such as pitch-angle scattering and precipitation loss to the atmosphere, heating and acceleration of particles by the absorption of wave power, as well as radial transport across L-shells.

As a consequence, our ability to accurately model the dynamic variability of large plasma structures such as the radiation belts during geomagnetically active periods, depends directly on (A) how well we understand the global distribution, properties, and variability of the plasma wave power, as well as (B) how well we understand the effect of these waves on the particle populations.

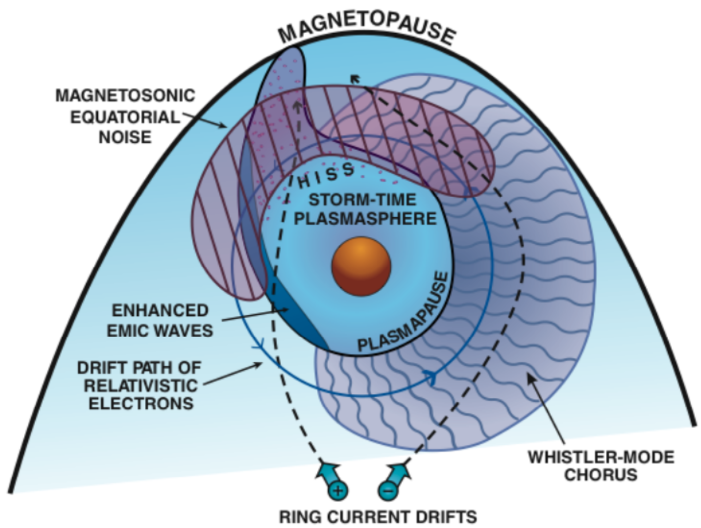


Figure 1: Schematic diagram showing the spatial distribution of important waves in the inner magnetosphere, in relation to the plasmasphere and the drift-paths of ring-current (10-100 keV) electrons and ions and relativistic (≥ 0.5 MeV) electrons.

Figure 1 shows an example of a few of the wave types that are known to play a critical role in controlling radiation belt and ring current dynamics. These include whistler-mode chorus, hiss, electromagnetic ion cyclotron (EMIC), and magnetosonic (MS) waves in the "high" frequency range (ironically called Very Low Frequency – VLF waves), as well as ultra-low frequency (ULF) oscillations that bathe the entire magnetosphere in wave power, or occur in episodic bursts associated with solar wind pulses. Each class of wave is believed to exert a particular effect on the radiation belts, and affect a specific population (i.e., in energy and pitch-angle space) of particles causing acceleration or a loss.

Each of these waves types exhibits its own particular variability during the course of geomagnetic storms, manifested in its spatial distribution, power, and polarization characteristics, which in turn determine the role the waves play in radiation belt dynamics, and the population of particles it affects. When all the different wave types are considered as a whole, the balance between acceleration and loss processes is altered and the net outcome on the radiation belt dynamics becomes notoriously difficult to predict. There are important challenges embedded in virtually every step of the process described above. Although significant progress has already been made in understanding the role of certain wave-particle interactions , much work remains to be done, as we outline next.

2. Accomplishments and outstanding problems

We summarize the proposed contributions of theory and modeling efforts in the next decade of radiation belt and ring current research using six focus areas of study. In each case, we briefly summarize the results and achievements to date (made predominantly in the past decade) and highlight areas where more detailed work is required.

2.1. Predicting the outcome of geomagnetic storms on the radiation belts

At the present time, it is not possible to reliably predict the outcome of a given storm on radiation belt fluxes. This was elegantly demonstrated by Reeves et al. [2003] who showed that for similar sized storms, the radiation belts after the storm sometimes increased relative to pre-storm levels, sometimes decreased, and sometimes remained essentially unchanged.

An overarching goal of the theory and modeling effort is to understand and ultimately predict the precise dynamical variability of the radiation belts. In order to do so, it is imperative to understand the distribution and variability of the wave distribution that controls radiation belt dynamics, as well as the precise effect of each wave on the particle population. These goals are articulated in the remainder of the focus areas described below.

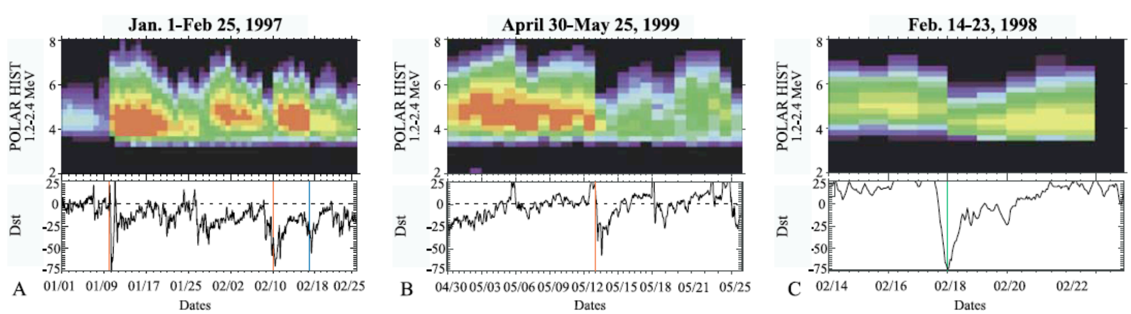


Figure 2: (From Reeves et al. [2003]) Similar sized storms can produce (A) a net increase (B) a net decrease, or (C) have no effect in radiation belt fluxes

2.2 Producing a detailed specification of the wave distributions

As mentioned above, a key component in understanding radiation belt dynamics, is the precise quantification of the wave distribution that controls it. Put succinctly, we aim to evaluate the function:

$$W = f(L, MLT, \lambda, f, \psi, \phi, M, D, t) \qquad (1)$$

Where W is wave power as function of:
- spatial location, i.e., L-shell (L), Magnetic Local Time (MLT), and latitude (λ)
- **k**-space, i.e., wave frequency (f), and wave normal angles (ψ, φ)
- wave mode M, which includes chorus, hiss, ULF, EMIC and MS waves
- Duty cycle D, i.e., occurrence rate
- and time t, usually as a function of storm or substorm phase.

We show a number of examples of 'partial' wave distributions, i.e., partial relative to (1), in Figure 3 from both observational and model studies. Modeling is needed to supplement and interpolate the point measurements that are made by satellites, particularly as pertains to polarization characteristics (i.e., distribution in k-space). Much needed effort should also be directed towards understanding the process of wave excitation and saturation numerically/analytically.

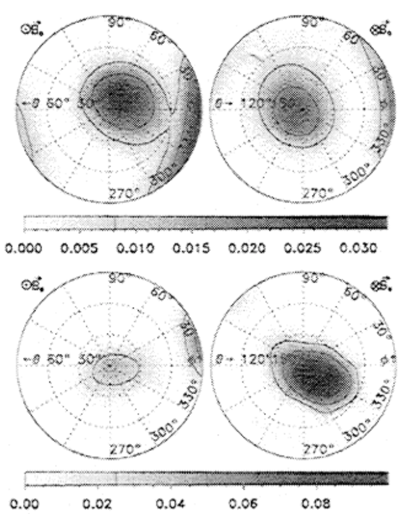
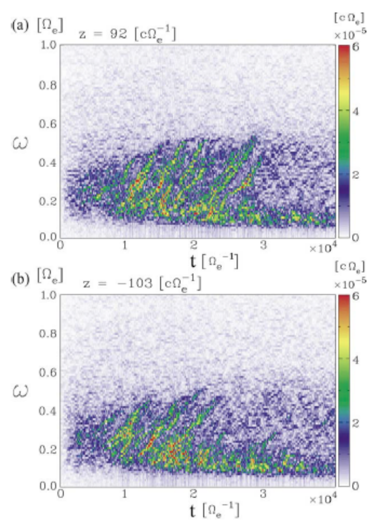
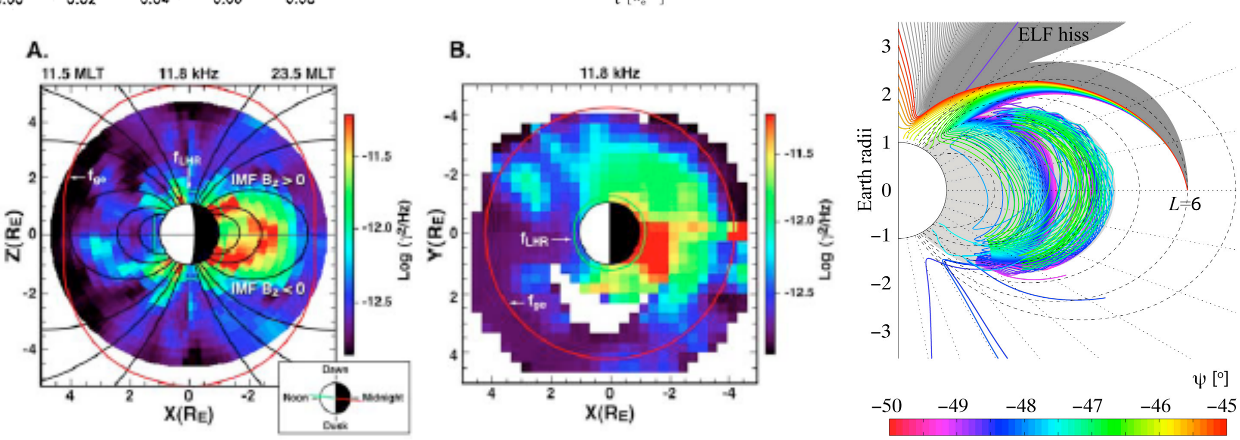



Figure 3: Various examples of measured and modeled wave distributions. Clockwise from left: (i) DE 1 and IMAGE wave power in meridional and equatorial planes [Green et al., 2005], (ii) WDF distribution of hiss in k-space [Santolik et al., 2001], (iii) Simulation of chorus generation [Katoh and Omura, 2008], and (iv) Raytracing simulation of chorus and hiss [Bortnik et al.. 2009].



2.3. Determining the effects of different waves on radiation belt dynamics

Wave distributions such as those in Figure 3 are used to calculate diffusion coefficients, which are then bounce- and drift-averaged, and used in Fokker-Planck diffusion codes to solve for the evolution of the phase space density of electrons or ions. This approach presupposes a distribution of small-amplitude, phase-incoherent waves that qualitatively produce a diffusive response in interacting particles. In this quasilinear theory (QLT) framework, it is generally agreed that EMIC and hiss waves act predominantly as loss process for energetic electrons, whereas chorus and MS waves predominantly accelerate those particles. However, the precise effect of each wave, and the population of particles (in energy and pitch angle space) that they affect depend critically on the wave's distribution (equation 1 above), and the balance between different effects depends on the variability of the wave distributions during the course of a storm.

In recent years, a number of 3D diffusion codes have been developed, which have contributed a great deal to understanding the roles played by various waves. However, with improved wave distributions as inputs, this understanding is expected to progress significantly, and especially so under dynamic conditions when the different wave distributions evolve.

2.4. Assessing the role of non-diffusive processes

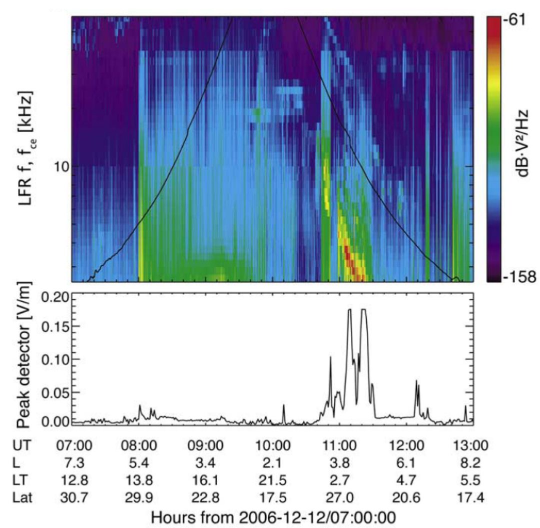


Figure 4: Observation of large amplitude whistler waves (~1 nT) on STEREO B (from Cattell et al. [2008].

Currently, the main theoretical tool used in studying global radiation belt dynamics is QLT which strictly applies only to small amplitude, incoherent waves. However, many of the waves that are currently being analyzed do not fit this description. Most notably, Figure 4 shows an example of the recently discovered large amplitude whistler waves, which are incidentally also narrowband and coherent and thus do not fit into the QLT framework. Indeed, recent work has shown that these waves produce a qualitatively different response in the interacting particles than the predictions of QLT [e.g., Bortnik et al., 2008; Kellogg et al., 2010]. Such nonlinear interactions are more appropriately described by test-particle simulations. Another example is scattering by MS waves, which was recently shown to produce a class of non-resonant scattering called transit-time diffusion [Bortnik and Thorne, 2010]. Clearly, the particle response to the wave field is not entirely linear and diffusive, and it is a major challenge of the theory and modeling effort to fully understand and quantify the role of non-diffusive scattering, particularly so in the light of improved wave distributions.

2.5. Understanding radial transport

The generally accepted view of radial transport in the radiation belts (up until approximately a decade ago) was that ULF fluctuations caused a steady inward radial diffusion from a source of particles at higher L-shells [e.g., Schultz and Lanzerotti, 1974]. That view, however, has recently been extensively revised, if not transformed.

Recent modeling work (e.g., Figure 5) has shown that radial transport can be very rapid, and coherently accelerate electrons to ~MeV energies in a non-diffusive process [e.g., Li et al., 1993; Elkington et al., 2004]. Moreover, radial diffusion can act as a loss mechanism, transporting particles from their low L energization region (L~4-6), outward to the magnetopause where they can be lost [Shprits et al, 2006].

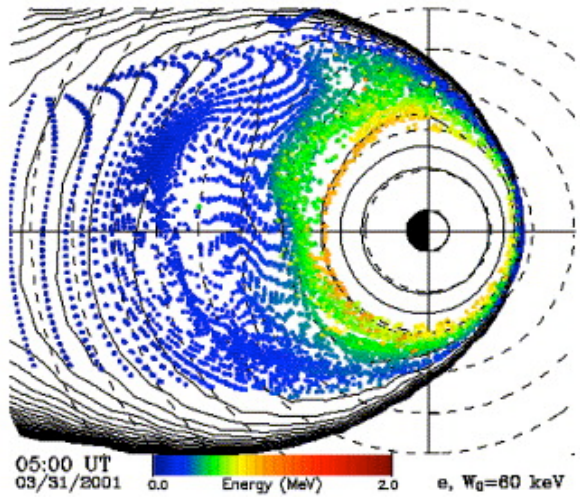


Figure 5: A test-particle based simulation of the injection and acceleration of plasmasheet electrons to MeV energies (from Elkington et al. [2004])

Although considerable modeling and theory work has already been devoted to understanding the role of radial transport in the radiation belts, much work still remains to be done on reliably predicting the precise mechanism and extent of the radial transport for a given storm or set of conditions, which is a modeling goal of this white paper.

2.6. Understanding the role of plasmasheet electrons

Although the drift motion of individual plasmasheet electrons in a prescribed E and B field is well described and understood, the role of the population of plasmasheet electrons in radiation belt dynamics is nevertheless not especially clear. Plasmasheet electron injections are known to be associated with radiation belt enhancments, but the precise mechanism could be one (or all) of the following:

1. As the population of seed electrons (~10-100 keV) to be accelerated by waves.
2. As the source of free energy to excite waves such as chorus, that will then accelerate the existing seed population of electrons
3. As the sink of wave energy in the form of Landau damping, that shapes the spatial distribution and characteristics of the waves, and thus controls the population of electrons that are accelerated.

One of the objectives of the theory and modeling effort will be clarifying the role of plasmasheet injections in radiation belt dynamics.

3. Recommended funding

Using the six focus areas summarized above as the targets of the theory and modeling effort in the next decade of radiation belt research, we urge the decadal survey committee to commit an appropriate level of funding to allow meeting these goals. We recommend that funding be commensurate with the typically large budgets set aside for observational missions, and further that the funding be balanced to include a good mix of:

1. Fundamental theory: developing and extending our current methods and techniques at the most basic level, as the catalyst of future observational campaigns.

2. Mission-specific T&M: developing T&M that is focused on supporting a specific mission, developing appropriate modeling tools that produce outputs best suited for observational testing by a specific mission.

3. High risk T&M: developing models and techniques that are inherently risky by nature, but with a potentially large payoff. This is contrasted with the generally conservative and incremental T&M efforts in points 1 and 2 above.

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Magnetospheric Causes of Saturn's Pulsar-Like Behavior

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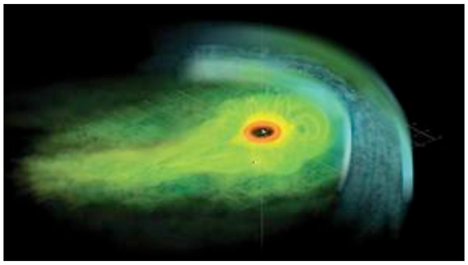

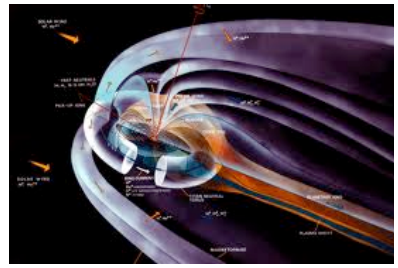

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Abstract

Because Saturn is a giant gaseous planet, visual observations cannot be used to determine accurately its internal rotation rate. Just as radio wave periodicities are thought to represent the rotation periods of the parent bodies of pulsars throughout our galaxy, Saturn kilometric radiation (SKR), an intense radio emission discovered during the 1980-1981 Voyager flybys, has a periodic modulation that represents what has until recently been considered the best available measure of the planet's rotational period. The SKR modulation period, determined by Voyager to be 10 hours, 39 min, 24 ± 7s, is currently the official internationally accepted rotation period of Saturn. Surprisingly, recent radio measurements from the Ulysses and Cassini spacecraft indicate that the SKR modulation period varies by as much as 1% on time scales of years, with current estimates showing a longer period of about 10 hours, 45 min. Because of Saturn's large inertia, the internal rotation period cannot possibly have changed by such a large amount, and so this finding represents a truly outstanding mystery. Given the importance of radio wave diagnostics of many phenomena that occur throughout the Universe, the resolution of this mystery has broad implications. Analysis of Cassini plasma, energetic particle and field data supplementing the radio measurements has shown that many magnetospheric phenomena display periodicities with periods similar to those of SKR. These observations, combined with the fact that the SKR period shows likely seasonal dependence, indicate a possible magnetospheric and/or ionospheric influence on the periodicity. Numerous models have been advanced to explain the various observed periodicities, but we suggest that a viable model should explain both the SKR source and the various observed magnetic-field and particle signatures. We do not

anticipate that this question will be answered with Cassini, primarily because of the limitations inherent to the single vantage point available from one spacecraft. This white paper proposes a three-spacecraft mission that we believe will answer the outstanding questions concerning Saturn's periodicity. Two small spacecraft will make magnetic field, plasma, energetic particle, and radio wave measurements from low-inclination orbits with lines of apsides approximately 30° - 45° apart. A third slightly larger spacecraft in an elliptical polar orbit will provide global ENA and photon imaging of energetic ion populations and of water-group neutrals and ions (e.g., OH and OH^+*), respectively, and also make magnetic field and radio wave measurements. This set of three spacecraft will test most, if not all, of the models of Saturn's periodicity that have been proposed to date based on Cassini data. The challenge will be to accomplish the mission within available resources, which will be achieved by designing the mission to be accommodated with solar arrays, direct transmission of data from each spacecraft to DSN, and direct injection of the three spacecraft into Saturn orbits with no subsequent maneuvers. It is understood that the Heliophysics Division at NASA is unlikely to provide sole support for a mission as ambitious as this one with 3 spacecraft. However, this science issue is of such import and of such cross-disciplinary interest that it could become a part of a broader, inter-Division effort. At a minimum, this science issue should be documented in any report that identifies the most outstanding science issues of our discipline. The results from this mission would not only help solve one of the greatest mysteries of the Saturnian system, they would also shed light on a similar phenomenon in Jupiter's inner magnetosphere (system IV periodicity). The results from this mission would also greatly enhance our understanding of mass and momentum coupling between a parent body and its magnetosphere in rapidly rotating planetary and astrophysical objects.*

I. Important Scientific Questions About Saturn's Periodicity

Cassini radio-wave measurements have established that Saturn Kilometric Radiation (SKR) is modulated with a period near the planetary rotation rate. Rather than being a rotating beacon, as is the case for pulsars, the maxima occur in the time domain and emanate from the low-altitude portion of magnetic field lines that reach near the magnetopause at late morning local times [*Gurnett et al*., 2007]. So, unlike the Earth, whose auroral kilometric radiation (AKR) only occurs on the night side, Saturn's SKR occurs primarily on the day side. This difference has not been explained; however, the circular polarization features of SKR are consistent with its generation by the cyclotron maser instability, which occurs in regions of strong field-aligned currents, as is the case for AKR. The regular periodicity of SKR led to the development of a Saturn longitude system during the pre-Cassini epochs. During the Voyager epoch, it was taken as gospel that the SKR period represented the rotation period of those internal regions of Saturn responsible for the generation of Saturn's internal magnetic field. However, Cassini scientists were shocked to find that this assumed-to-be "rock solid" measure of Saturn's internal rotation period was varying to an inexplicable degree. This finding led to a revision of the longitude system to account for the gradual increase of the period [*Kurth et al*., 2008]. However, even more surprising has been the finding that SKR periodicities arising from northern hemisphere measurements are different from SKR periodicities arising from southern hemisphere measurements [Gurnett et al., 2009].

Use of the SKR longitude systems has revealed periodicities in many other magnetospheric observables (magnetic field, plasma, energetic particles) that match those of SKR. These results have led to several suggestions about what might cause the various periodicities and how these causes might be shared with SKR, which is a crucial test for any viable model. Most explanations rely on the fact that the magnetosphere is rotationally dominated so that structures such as plasma and energetic particle populations, convection patterns, and field-aligned current systems are expected to rotate past Cassini, whose motion is generally much slower than corotation. But other phenomena, such as a hinged current sheet, a subsurface magnetic anomaly, and upper-atmospheric zonal winds have also been suggested as causes for the widely-observed periodicities. After more than six years of observations with Cassini, no strong consensus has been achieved on why Saturn exhibits its mysterious pulsar-like behavior and none is anticipated.

A. Why is SKR generation strongly peaked around a narrow range in longitude and local time? This question is perhaps the most fundamental one concerning SKR periodicity. One of the early suggestions, based on Pioneer and Voyager magnetic field observations, was that a localized pressure increase from a longitudinally restricted equatorial anomaly (likely magnetic) launches compressional MHD waves [*Espinosa et al*., 2003] that propagate across magnetic field lines along an Archimedes spiral, causing magnetic perturbations and eventually, when they reach the magnetopause, triggering SKR. However, the gradual lengthening of the SKR period has diverted attention away from sources such as magnetic anomalies that are tied to the planet itself. Nonetheless, further searches for magnetic anomalies will be conducted in the polar-orbit phase of Cassini and would be continued in the mission we propose.

Another model that could be tested with our mission is based on a rotating interchange-driven two-cell convection system that sends plasma from the Enceladus torus out along a spiral path to the magnetopause [*Gurnett et al.*, 2007]. This model requires a means to synchronize the region of outflow from the two-cell convection with SKR longitude and to maintain this synchronization for long periods of time. This means could involve a natural long-term stability of the convection pattern, a pressure source such as suggested by *Espinosa et al.* [2003], or another mechanism for enhancing interchange at a certain SKR longitude.

B. What causes periodic magnetic field perturbations in synchronism with SKR? In addition to the *Espinosa et al.* [2003] equatorial anomaly model, other more recent suggestions have been made. These include the model of *Khurana et al*. [2009], which is based on the tilt of Saturn's rotational axis with respect to the ecliptic plane combined with a pressure anisotropy in the equatorial ring current. The neutral sheet is predicted to be deflected by solar-wind pressure to a greater or lesser degree depending on the anisotropic plasma pressure from the ring current. The resulting flapping of the neutral sheet has been shown to be capable of replicating observed magnetic field signatures, while the ring-current anomalies themselves could produce SKR modulation when they intersect the magnetopause.

Andrews et al. [2010] developed a model based on Cassini magnetic field data that involves two rotating field-aligned current systems connecting the northern and southern hemispheres, one inside 15 Rs (connected to the Enceladus torus) and one outside 15 Rs (connected to the nightside plasma sheet). This model has some characteristics in common with the *Gurnett et al.*

[2007] model (i. e., a twin vortex and a localized plasma enhancement); and since it contains field-aligned currents, it could be directly consistent with the generation of SKR. An enduring puzzle remains that the plasma is known to subcorotate in most of the magnetosphere (below the SKR period). It is difficult to understand how structures such as a twin vortex or a field-aligned current system embedded in a subcorotating plasma produce an SKR emission at the SKR period.

C. What causes the spiral structures in plasmas and energetic particles that extend to distances >50 Rs in Saturn's magnetosphere, and how are they related to SKR? Periodicities observed in energetic electrons by *Carbary et al*. [2007] and plasma ions by *Burch et al*. [2008] have been shown to be consistent with enhanced fluxes organized along a spiral pattern in SKR longitude extending from 10 Rs to beyond 60 Rs with the spiral anchored near the longitude of the previously observed plasma density enhancements at 330° longitude [*Gurnett et el*., 2007]. *Burch et el*. [2008] have also shown that beyond 35 Rs plasma and magnetic-field signatures consistent with plasmoids [*Jackman et al*., 2007; *Hill et al*., 2008] were situated along this spiral structure. These features were observed once per Saturn day as the supposed spiral rotated past Cassini at various distances and were further organized on a statistical basis to show that the pattern persists over periods of a few years. *Burch et al*. [2009] examined the base region of the spiral further and found that on a statistical basis ion fluxes showed a cam-like structure involving enhanced ion fluxes in the SKR longitude range of the base region, suggesting enhanced plasma outflow from the inner magnetosphere in that sector. However, since the two-dimensional spiral pattern was deduced from single-point measurements, its existence cannot be uniquely determined. For example, it could have been caused by periodic encounters with the neutral sheet [*Jackman et al.*, 2009], which itself may be spatially organized by SKR longitude. The existence of the spiral structures could, however, be tested definitively by measurements from two spacecraft positioned at different radial distances and longitudes as would be provided by our proposed mission. In addition, with two spacecraft situated along the spiral, unique determination of the plasma and magnetic-field signatures of the suggested plasmoids and the associated reconnection events could be made. Reliable plasma velocity measurements would be required to understand how the spiral can remain organized by the SKR longitude in the subcorotating plasma.

D. What causes the periodic ENA enhancements that appear between midnight and dawn and rotate into the late morning magnetopause where SKR is generated? *Mitchell et al*. [2009] have used ENA images to show that under some magnetospheric conditions protons and oxygen ions are accelerated once per Saturn magnetosphere rotation, at a preferred local time between midnight and dawn. They suggested that these events result from current sheet acceleration in the 15–20 Rs range, probably associated with reconnection and plasmoid formation in Saturn's magnetotail. Simultaneous auroral observations by the Hubble Space Telescope (HST) and the Cassini Ultraviolet Imaging Spectrometer (UVIS) suggested a close correlation between these dynamical magnetospheric events and dawn-side transient auroral brightenings. Many of the recurrent ENA enhancements coincided closely with bursts of SKR, leading Mitchell et al. to suggest that a rotating field-aligned current system linked to the ionosphere drives the auroral and SKR processes. Further examination of these events would be optimized by using the better vantage point provided by a polar orbit giving ENA fields of view extending outward to >20 Rs in the equatorial plane. Combining such ENA images with in-situ particle measurements at various distances in the equatorial magnetosphere would provide a unique systems-level approach to determining why and how these important ion energization events occur.

E. Why do northern and southern hemisphere SKR pulses have different periods? Recent radio observations from the Cassini spacecraft [*Gurnett et al*., 2009] have revealed that SKR emissions from the northern and southern hemispheres have periods near 10.6 and 10.8 hours, respectively. Gurnett et al. concluded that this north-south asymmetry in the SKR period has potentially important implications for the question of how angular momentum is transferred from the interior to the magnetosphere. For the 5-year interval analyzed, the southern hemisphere was sunlit while the northern hemisphere was in darkness, which would cause the ionospheric conductivity to be higher in the southern hemisphere, leading to better coupling between the auroral plasma, in which SKR is generated, and the equatorial plasma disk in the southern hemisphere. Gurnett et al. suggested that the decoupling mechanism might involve parallel potential drops but note that other mechanisms may be important, and these might include hemispheric differences in zonal neutral wind speeds.

II. Strategy for Solving the Mystery of Saturn's Pulsar-Like Behavior

Our strategy involves the implementation of a three-spacecraft mission. This mission would include an imaging spacecraft in polar orbit and two in-situ spacecraft in different low-inclination orbits. The spacecraft would be small and contain minimal payloads designed to investigate specifically the magnetospheric and radio-wave periodicities that have been observed, although by their very presence they would be capable of accomplishing a much wider range of magnetospheric physics objectives.

The polar satellite would contain an imager capable of detecting water-group ions and neutrals (e. g., OH and OH^+, with several other possibilities) and an ENA imager to obtain images of both light and heavy ions in the equatorial plane. The two imagers would also be used to monitor the supply of neutrals and plasma from the south polar plume of Enceladus. These two imagers would be supplemented by a magnetometer and a radio-wave receiver for SKR, auroral hiss, and other emissions. In addition to measuring field-aligned currents, the magnetometer would be used to search for main-field magnetic anomalies.

The two equatorial satellites would each carry a magnetometer, a radio-wave receiver, a plasma instrument, and an energetic particle instrument. As shown by the Cassini plasma data, because of the rotation-dominated environment, composition on the particle instruments would be optional since the water-group ions are clearly separated from protons by virtue of their equal convection velocities.

A. Mission design. The three spacecraft would travel to Saturn as a unit and then be injected sequentially into their final orbits. The imaging spacecraft would be injected into a high-inclination elliptical orbit (60 - 90 deg. inclination) with apoapsis of ~20 Rs. The two equatorial spacecraft (inclination <10°) would be injected one at a time into highly elliptical orbits with apoapsis of ~50 Rs. Their lines of apsides would be separated by 30-45°, one premidnight and one postmidnight. Any perturbations caused by moons would not be corrected for because the exact relative placement of the two spacecraft is not crucially important.

All three spacecraft would be solar-powered sun-pointed spinners with spin periods of a few minutes. Juno-type deployable arrays (three panels with total area ~45 m^2) would be used to provide >100 W of power. Each spacecraft would transmit data directly to Earth at >1000 bits/s using a 25 W transmitter and a 70-m DSN antenna [*Bolton and Owen*, 2006].

B. Scientific payloads. All instruments have significant heritage from Cassini, IMAGE, ST-5, and many other previous missions. Because the spacecraft will spin, there will be no need for scan platforms. The payloads for the three spacecraft are shown in **Table 1**.

Table 1

Instrument/Heritage	Parameters	Mass (kg)	Power (W)	Polar S/C	Eq. S/C
Magnetometer	Flux gate, 40 - 40,000 nT	2	2	X	X
Waves Receiver	10 - 10^6 Hz (SKR and auroral hiss)	8	10	X	X
Plasma	electrons/ions, 10 eV - 30 keV, 5° x 360°, 3D in one-half spin, composition optional	5	5		X
Energetic Particles	electrons/ions, 20 keV - 200 keV, multi-SSDs, composition optional, 3D in one spin	5	5		X
Water Group Imager	Imaging at 308 nm (OH) and 385 nm (OH^+), 30° x 84°, 360° x 84° in one spin	15	9	X	
ENA Imager	20 keV - 200 keV, light and heavy ions, 90° x 120°, 360° x 120° in one spin	7	4	X	

C. Investigation approach. A suggested approach to answering the major science questions we have identified is shown in **Table 2.** In each case the question can be answered with the very focused payloads described in **Table 1** on three small spacecraft in carefully selected orbits.

III. Conclusions

Cassini has provided a vast amount of new information on the pulsar-like behavior of Saturn's magnetosphere. Because of the limitations of a single vantage point, an understanding of the cause of Saturn's periodicities can not be fully achieved with Cassini data. A carefully focused multi-spacecraft mission can answer most of the outstanding questions, but in order to fit within anticipated resources the mission will have to use small, solar-powered spacecraft with minimal payloads, low data rates and no orbit-adjust capability. All of the necessary instruments have extensive heritage and can be simplified with respect to their use on Cassini by virtue of the spinning spacecraft. While we understand the tremendous challenges of this mission from technical, programmatic and cost perspectives, we believe that the greatest value of the heliophysics discipline in the future will come from tackling the most compelling scientific problems that have the broadest interdisciplinary impact.

Table 2

Science Question	Approach
A. Why is SKR generation strongly peaked around a narrow range in longitude and local time?	• Use multi-point SKR measurements for direction finding. • Use multi-point magnetic-field measurements for global field-aligned current detection. • Use low-altitude magnetic-field measurements to search for magnetic anomalies. • Use imaging of OH^+ emissions to detect localized outflow. • Use ENA imaging to detect ring current anisotropies and acceleration sites and track drifting energetic particle clouds
B. What causes periodic magnetic field perturbations in synchronism with SKR?	• Use multi-point SKR measurements for direction finding. • Use multi-point magnetic-field measurements for global field-aligned current detection. • Use plasma and magnetic-field measurements at two locations in the equatorial plane to test for neutral-sheet flapping and map the longitudinal variations of plasma density and pressure. • Use ENA imaging to search for ring-current anisotropies.
C. What causes the spiral structures in plasmas and energetic particles that extend to distances >50 Rs in Saturn'smagneto-sphere, and how are they related to SKR?	• Use sequential crossings of the spiral structure with two spacecraft at different radial distances to test for existence of the predicted spiral structure and its rotational velocity. • Use plasma, energetic particle, and magnetic-field measurements at two locations along the spiral structure to test for reconnection signatures. • Search for the source of the spiral structure with photon imaging of OH^+ circulation and outflow.
D. What causes the periodic ENA enhancements that appear between midnight and dawn and rotate into the late morning magnetopause where SKR is generated?	• Image ENAs from high latitudes to detect acceleration and drift events and monitor the source strength at Enceladus. • Simultaneously measure plasmas and energetic particles at two points along the predicted spiral paths that bracket the acceleration event to test for reconnection signatures. • Use multi-point SKR measurements to determine the location of the emissions and related the intensities to ENA interactions with the magnetopause.
E. Why do northern and southern hemisphere SKR pulses have different periods?	• Use multi-point SKR measurements to determine northern and southern hemisphere periods. • Use multi-point magnetic-field measurements to determine northern and southern hemisphere field-aligned currents.

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Understanding Mercury's Space Environment-Magnetosphere-Exosphere System: A Unified Strategy for Observational, Theoretical, and Laboratory Research

A Concept Paper Submitted to the Heliophysics Decadal Survey

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1. Introduction

The interaction of Mercury's magnetosphere and surface with the space environment is highly dynamic due to Mercury's weak dipole magnetic field and the relatively strong interplanetary magnetic field and high solar wind density at Mercury's orbit. The resulting balance between the solar wind dynamic pressure and Mercury's magnetic pressure results in a magnetopause boundary nominally at less than one planetary radius, and at times pushed to the planet's surface. The varying Interplanetary Magnetic Field (IMF), and the resulting reconnection vector field creates a highly variable pattern of solar wind precipitation onto the surface and, therefore, a variable source of protons and heavy ions to the magnetosphere that modifies its structure. Understanding the coupling of the space environment, magnetosphere, exosphere, and surface requires a comprehensive program of observational, theoretical, and laboratory research.

2. Mercury's Exosphere

Mercury's "surface-bounded exophere" is collisionally thin down to the planet's surface. As such, the composition and dynamics of the exosphere represent the ongoing interactions between solar radiation, the solar wind, Mercury's magnetosphere, the meteoroid and dust environment, and the surface. Understanding this complex system requires (a) ground- and space-based observations of the multiple exospheric constituents, (b) laboratory and *in-situ* measurements that can quantify the source and loss processes, including micrometeoroid and meteoroid flux, (c) models of the interaction between the interplanetary magnetic field with Mercury's internal dipole, and (d) models following exospheric material which include the interaction with the surface, ionization and pickup by Mercury's magnetic field or the IMF, and the escape of neutrals and ions into the extended tail.

Exospheric H and He were discovered by the ultraviolet airglow spectrometer onboard Mariner 10. Although upper limits were placed on emission from O, Ne, Ar, Xe, and C [Broadfoot et al. 1974;1976], these species have never been observed either in-situ or remotely. Additional species were observed from the ground, beginning with the discovery of Na and K in the

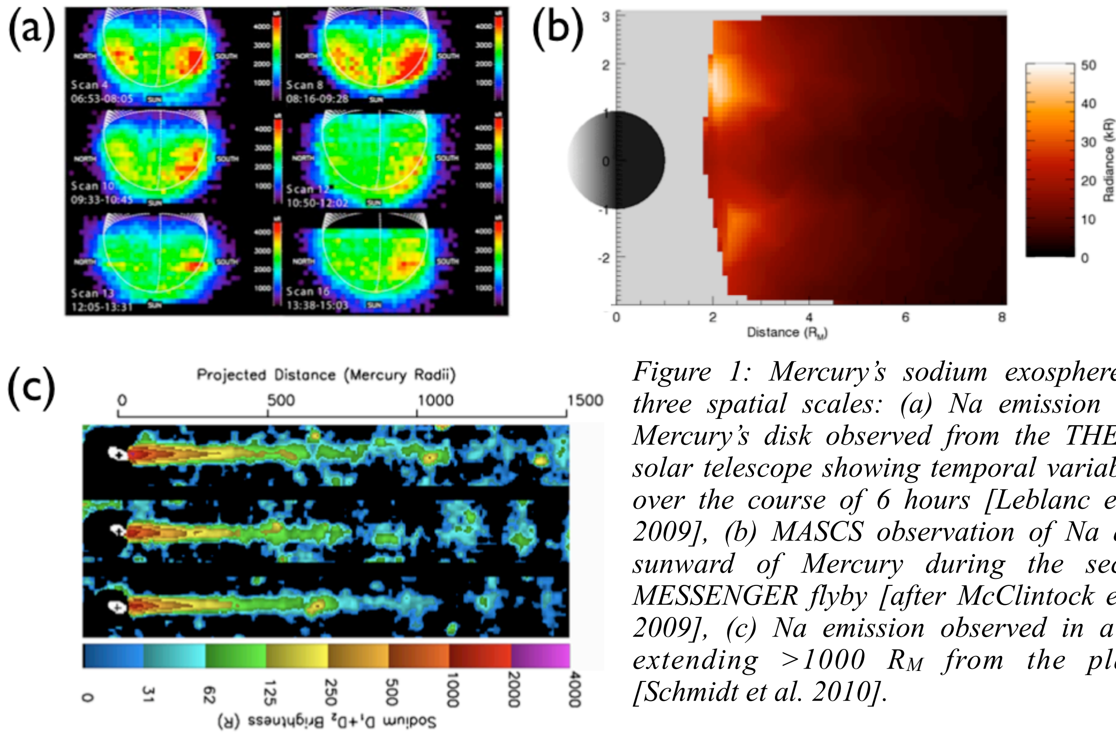

Figure 1: Mercury's sodium exosphere on three spatial scales: (a) Na emission over Mercury's disk observed from the THEMIS solar telescope showing temporal variability over the course of 6 hours [Leblanc et al. 2009], (b) MASCS observation of Na anti-sunward of Mercury during the second MESSENGER flyby [after McClintock et al. 2009], (c) Na emission observed in a tail extending >1000 R_M from the planet [Schmidt et al. 2010].

mid-1980s [Potter and Morgan 1985;1986], and recently, Ca, [Bida et al. 2000], and Al, Fe and Ca^+ [Bida and Killen 2010]. The Mercury Atmospheric and Surface Composition Spectrometer (MASCS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft added Mg and Ca^+ to the list of confirmed exospheric constituents [McClintock et al. 2009] while also providing high spatial resolution maps of Na and Ca, and making the first spectral detection of the ionospheric species Ca^+ [McClintock et al. 2008;2009; Vervack et al. 2010].

Due to its large cross-section for resonant scattering in the visible, Na is the most extensively studied species in Mercury's exosphere and has been observed at a number of spatial scales (Figure 1). Observations of the near surface component (Figure 1a) reveal an approximately 1200 K Na exosphere with the Na gravitationally bound to Mercury's disk which can vary on time scales of hours, approximately the photoionizaton lifetime. MASCS data (Figure 1b) from the MESSENGER flybys of Mercury have primarily been sensitive to escaping material that populates a tail created by radiation pressure, extending anti-sunward over 1000 R_M ($2.4x10^6$ km, where R_M is Mercury's radius, 2440 km) (Figure 1c) [Baumgardner et al. 2008; Schmidt et al. 2010]. Ca and Mg have been much less extensively studied due to their fainter emissions and the difficulty in detecting them from Earth. The MESSENGER flybys, however, have indicated that the spatial distributions of these species differ significantly from Na and from each other in ways that cannot be explained by differences in the radiation acceleration and/or photoionization loss; i.e., the morphological differences imply differences in the source mechanisms and distributions over the surface.

Temporal variability of the exosphere, on time scales ranging from hours to months, is probably associated with the solar wind interaction with Mercury's magnetosphere, with variations in the UV radiation, and with the interplanetary dust distribution [e.g., Kameda et al. 2009]. Magnetic reconnection allows ion precipitation through the cusps of the magnetosphere onto the surface creating regions of possible ion sputtering, ion-enhanced photon-stimulated desorption (PSD), or electron stimulated desorption (ESD). Regions of high latitude enhancements in Na and K are often seen in ground-based data (e.g. Fig. 1a), and MASCS saw intense emission directly above the poles from Na, Mg and Ca [Vervack et al. 2010]. Whether this is related to magnetospheric convection is a matter of debate at present.

In order to understand the evolution of the near-surface and escaping exosphere, we require a continued program of ground-based observing combined with data from the MESSENGER and BepiColombo missions. While MASCS will make high spatial resolution observations of many exospheric species (both currently known as well as predicted constituents such as O and S) and BepiColombo will have a dedicated Na imager (Mercury's Sodium Atmosphere Spectral Imager, MSASI), only ground-based studies can provide a global context in which to interpret the data. This has been demonstrated by Mouawad et al. [2010] who could constrain parameters related to the gas-surface interaction using simultaneous spacecraft and ground-based observations of the escaping and bound components of the sodium exosphere.

3. Magnetospheric Interactions

Among the most important early results from MESSENGER was the finding that, although its intrinsic field appears to be unchanged since the days of the Mariner 10 encounters, Mercury's magnetosphere is extremely variable on timescales of minutes and is much more responsive to the IMF direction and the effects of reconnection than that of Earth or the other magnetized planets [Slavin et al. 2009; Slavin et al. 2010a; Slavin et al. 2010b].

The variable response of the magnetosphere to external drivers was most evident in MESSENGER Magnetometer (MAG) data from the second (M2) and third (M3) flybys, when steady southward (M2) and variable north-south (M3) IMF conditions were encountered. During MESSENGER's second flyby, a large magnetic flux transfer event, estimated to be ~1 R_M in diameter, was observed in the magnetosheath, and a plasmoid and multiple traveling compression regions were observed in Mercury's magnetotail [Slavin et al., 2009]. During MESSENGER's third flyby, the magnetic field in the planet's magnetic tail increased during four separate instances by factors of 2–3.5 over intervals of 2 to 3 minutes. These were attributed to magnetic flux loading and then unloading of the magnetotail similar to magnetospheric substorms at Earth, but with much higher amplitude [Slavin et al. 2010b]. Flux Transfer Events, plasmoids, traveling compression regions, and magnetotail loading-unloading are all products of reconnection of the IMF with the planetary magnetic field.

With the magnetosphere being so "open", solar wind ion access to the surface has long being hypothesized to constitute an important source of Mercury's rarefied exosphere [e.g., Potter and Morgan 1990; Sarantos et al. 2001]. The timescale for circulation of plasma and magnetic flux from the dayside magnetosphere to the magnetotail and back, the "Dungey cycle," is very short at Mercury, only ~1–2 minutes. However, the timescale for exosphere-magnetosphere connection is the lifetime of neutral particles, which is typically tens of minutes up to a few hours. Therefore, changes effected in the magnetosphere by reconnection have an opportunity to alter the exosphere.

Although models of Mercury's magnetosphere have provided order of magnitude estimates of the precipitating solar wind flux during Mercury's year [Sarantos et al. 2007] and during specific

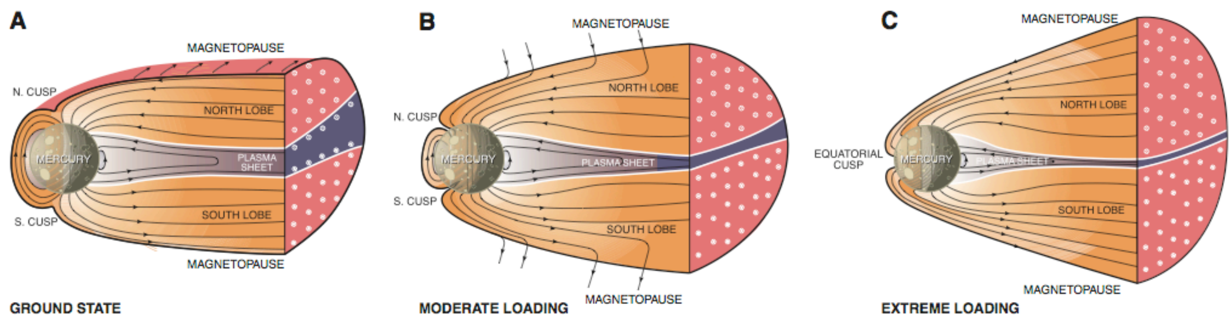

Figure 2: *Schematic view of Mercury's magnetosphere in its ground state (A), and during moderate (B) and extreme (C) tail loading observed by MESSENGER on 29 September 2009.*

observational campaigns such as the MESSENGER flybys [Benna et al. 2010], the short-term magnetospheric variability, which may prove to have the most important exospheric consequences, remains largely unstudied. Three related types of magnetospheric feedback to the surface are identified as follows. First, according to MESSENGER measurements, an average FTE diameter at Mercury is ~900 km, or ~0.4 R_M. This size corresponds to 28% of the 1.4 R_M mean distance from the center of the planet to the nose of the magnetopause [Slavin et al. 2009; Slavin et al. 2010a]. Obviously, such large FTEs significantly disturb the topology of the entire dayside magnetosphere, and, hence, the flux of solar wind ions reaching the surface, resulting in sputtering neutral atoms into Mercury's exosphere. Second, energy released by plasmoids is directed towards the planetary surface, and may prove to be an important, albeit episodic, source of the nightside exosphere. Third, the magnetotail flux content at the time of the peak loading events was estimated to be at least ~30%, and for the most intense event possibly 100%, of the available magnetic flux from Mercury [Slavin et al. 2010b]. Under such extreme conditions, Mercury's entire dayside magnetosphere may be eroded by reconnection, and up to 100% of the shocked solar wind may access the surface (Figure 2c). Neither the conditions of FTE generation at Mercury nor their effects of tail loading-unloading cycles on the exosphere have been modeled before.

3. Open Questions and Future Direction

The relative importance of proposed exospheric source processes is still an open question. Mechanisms which likely explain some of the observed neutrals include impact vaporization by micrometeoroid bombardment, ion sputtering, photon stimulated desorption, electron stimulated desorption, and thermal vaporization. However, a number of questions regarding each of these processes remain. A combination of continued observations, laboratory experiments, and numerical modeling is required to answer these questions.

The production rate of neutrals by micrometeoroid impact vaporization depends on the interplanetary dust density, composition, size distribution, and velocity distribution; the surface composition and thermodynamic properties; and the physics of the plume production, including energy distribution and chemical state of the vapor. While all of these factors have been studied, estimates for the amount of material produced by impact vaporization vary widely [e.g., Cintala 1992; Killen et al. 2004; Borin et al. 2010; Kameda et al. 2009; Burger et al. 2010], and significant uncertainties in all the important quantities remain.

The spatial distribution of a thermally desorbed component in the exosphere is also an open question. Dawn enhancements in the Na and Ca distributions have been observed which could be due to material building up on the night side and vaporizing upon emergence into sunlight [e.g., Sprague et al. 1997; Leblanc and Johnson 2010], however it is not known how quickly the Na or other species become depleted or if other processes act faster. Because thermal desorption is a lower energy mechanism (Mercury's surface temperature varies between about 90 and 750 K) than other proposed source processes, observations which constrain the ratio of bound to escaping atoms and velocity distributions could help determine the thermal flux from the surface. It is also unclear whether specific molecules can be thermally desorbed. Furthermore, at 750 K thermal desorption is so efficient that weakly bound atomic species will desorb completely very rapidly, leaving only more strongly bound sites. MASCS has shown that the Ca source is concentrated on the dawn hemisphere, but has a much higher temperature than a possible thermal source [Vervack et al. 2010]. Thermally desorbed molecular Ca followed by photodissociation would produce high energy atomic Ca [Killen et al. 2005]; however, it is clear that molecular Ca cannot be thermally desorbed at dawn temperatures.

Photon stimulated desorption (PSD) is the desorption of atoms from the surface as a result of electronic excitation of a surface atom by a photon [Yakshinskiy and Madey 1999]. This can be a very important process at Mercury where there is a high flux of photons with energies greater than the 4 eV required to eject a Na atom. Over most of the dayside, the PSD flux is limited by the rate at which Na can diffuse to the surface ($\sim10^7$ cm^{-2} s^{-1}) [Killen et al. 2004]. There are currently a number of uncertainties regarding PSD which require laboratory study. The PSD cross section increases between photon energies of 4 and 5 eV, but has not been measured for energies greater than 5 eV. Additionally, the threshold energies for species other than Na have not been determined, so it is not clear if there is a PSD contribution to the flux of other species to the exosphere. The energy distribution of desorbed atoms is also uncertain. Two energy distributions have been measured for Na, one approximately Maxwellian [Yakshinskiy and Madey 1999] and one with a high energy tail [Johnson et al. 2002], under different experimental conditions. Which applies best to Mercury, and whether either of these is appropriate for species other than Na, is not known.

Charged particle precipitation onto the surface can eject material into the exosphere by several mechanisms. Ion sputtering and electron stimulated desorption (ESD) are the direct ejection of neutrals through ion and electron bombardment, respectively. Sputtering is a process by which incident ions initiate a collisional cascade which can eject atoms or ions [Johnson 1990]. The efficiency of this process is not well measured, but the yield (number of sputtered atoms per incident ion) increases with ion mass and energy. ESD is similar to PSD with precipitating electrons initiating the electronic excitations which eject neutrals or ions [Johnson et al. 2002]. Ions and neutrals can be desorbed by electron impact, although the yields for different species are uncertain and required additional laboratory studies.

Ion precipitation can also increase the availability of Na or other species for desorption by other mechanisms such as PSD. Photon desorption only acts on the top few nanometers of the surface, so that the desorbed flux is limited by the diffusion rate of sodium from the interiors of grains to the surface. Ion precipitation can increase the sodium diffusion rate by supplying energy to heat the grains (which aids diffusion) and by forming defects in the lattice structure of the grains which allow Na to diffuse more freely. An increased PSD source rate appears to be correlated with regions where ions can reach the surfaces of the Moon [Sarantos et al. 2008] and Mercury [Burger et al. 2010]. Ion induced chemistry (chemical sputtering) has also been proposed as a means of creating Na and H_2O which can be desorbed [Potter 1995; Mura et al. 2009].

One of the largest impediments to progress in modeling the exosphere is the lack of relevant physical constants. At Mercury we have seen two refractory metals in the exosphere, Ca and Mg, both exhibiting extreme kinetic energy. Among the possible processes is dissociation of a diatomic molecule produced during an impact event [Killen et al. 2005]. In order to test this hypothesis we need measurements of dissociation cross sections, either from thermal effects or photo-dissociation. Similarly it has been proposed that both sodium and water are produced by chemical sputtering, but rates are not available for these reactions, and we do not know the velocity distribution of the desorbed neutrals. Electron stimulated desorption yields must be measured for a variety of atomic species, including Na, K, S, H_2, OH, O, He, Fe. PSD yields must be measured from both neutral and a charged surface, both before and after irradiation by protons.

The coupling of the exosphere and magnetosphere has not beenthorughly studied. The ionospheric electron density and temperature have not been measured since Mariner 10, so the contributions of electron impacts to the emission and loss is not known. Charge exchange rates have also not been determined, although Ca^+ was observed by MASCS and from the ground [Vervack et al. 2010; Bida and Killen 2010] and a number of pickup ions were detected close to the surface by the MESSENGER Fast Imaging Plasma Spectrometer (FIPS) (Na^+ or Mg^+, S^+, Ca^+ or K^+, O^+ or H_2O^+) [Zurburchen et al. 2008]. The importance of charge exchange is not known due to uncertainties in the relevant cross sections, ion and neutral abundances, and the ion energies. Additionally, the current models do not self-consistently treat the exospheric and magnetospheric dynamics, despite the fact that the neutral sources depend on the ion precipitation and magnetospheric dynamics will be affected by pickup of photo-ions. Photo-ions or electrons that return to the surface may eject additional neutrals and ions by sputtering or ESD, creating feedbacks between the exosphere and magnetosphere.

Modeling efforts are also limited by the lack of simultaneous observations of the magnetosphere and exosphere. The inputs to exospheric simulations of the MESSENGER data [Burger et al. 2010; Sarantos et al. 2010] have been limited to cases of steady, or quasi-steady, magnetospheric activity [Benna et al. 2010]. Without models, we cannot distinguish between temporal and spatial variability because the sparsity of MESSENGER flyby measurements requires that we combine all data together. These limitations will be addressed during orbital operations of MESSENGER and BepiColombo, but the consequences of magnetospheric activity will still be evident. A magnetospheric variability recovery time is ~2 mins, but, assuming important contributions by sputtering, the exosphere "memory" is ~10 mins to hours, the ballistic or photoionization lifetime of sputtered ejecta. Furthermore, if the main effect of the solar wind is to "prime" the surface and affect the efficiency of release from other processes as suggested for exospheric sodium, the exospheric consequences of magnetospheric variability will be even longer lasting.

4. Summary

The MESSENGER and BepiColombo spacecraft will explore Mercury's magnetospheric and exospheric dynamics, providing a wealth of new data. Interpreting this data correctly requires advances in laboratory measurements and numerical modeling. Below we summarize the experimental and theoretical work necessary for maximizing the scientiic return of the spacecraft data.

Required Observations

- Simultaneous ground-based and MASCS observations of exospheric Na
- MASCS monitoring of known exospheric and ionispheric species H, Na, Ca, Mg, Ca^+
- MASCS search for species which have not been observed by MASCS: O, S, Al, Fe, OH, as well as hypothesised or unexpected species (Mn, Hg, etc.)
- Exospheric Na imaging by MSASI on BepiColombo MMO
- Time resolved measurements of magnetospheric measurements by MAG
- Characterization of Mercury's ionosphere and pickup ion distributions by FIPS and MAG
- Quantification of the interplanetary dust distribution *in situ* by BepiColombo MMO Mercury Dust Monitor

Physical Constants to Measure

- Photoionization and dissociation cross sections for MgO and CaO
- Lifetimes for excited states, especially for molecules are produced during impacts
- Thermal dissication rates for MgO and CaO as function of temperature
- Surface sticking and thermal accommodation coefficients for all exospheric species
- Ion sputtering, PSD, and ESD yields for atoms, molecules, and ions as function of surface temperature and composition, incident ion and electon energy, etc.
- Ion-enhanced diffusion rates
- Rate coefficeints for chemical sputtering reactions (e.g., $2H + Na_2SiO_3 \rightarrow 2Na + SiO_2 + H_2O$)
- Effects of surface charging on desorption processes
- Surface binding energies for exospheric species
- Energy distributions for spcecies ejected by sputtering, PSD, ESD, and impact vapization

Numerical Modeling Goals

- Determine relative importance of different exospheric source processes
- Model the magnetospheric response to variable IMF on timescales comparable to or shorter than the "Dungey cycle"
- Quantify ion and electron precipitation rates and energy distributions for conditions encountered by MESSENGER
- Ion-neutral and electron impact reaction rates in exosphere based on ionosphere and exosphere observed by MESSENGER
- Understand the effects of pickup ions on magnetospheric dynamics
- Model Magnetic reconnection rates in the magnetosphere tail and impact on the exosphere and surface

The extreme variability seen in Mercury's tenuous atmosphere and magnetosphere seen during the MESSENGER flybys, the Mariner 10 flybys, and from ground-based observations in the interim between these two space missions, has opened a window into rapid communication of solar wind dynamic and magnetic pressure into a small magnetosphere. The rapid transfer of momentum via plasmoids, flux transfer events and waves in this small system allows us to study magnetospheric and ionospheric physics in a small rapidly evolving system in much the same way that biologists study evolution using species with a short lifetime. Our strategy for the future is to carry out simultaneous observations of this coupled system, surface-exosphere-magnetosphere, and to produce coupled models, acknowledging that each component of this system influences the other.

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White Paper:

"The development of a quantitative, predictive understanding of solar wind-magnetospheric coupling"

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Relevant panel themes:

Solar Wind-Magnetosphere Interactions (SWM)

Overview

Recent developments in the study of solar wind-magnetospheric coupling have raised questions about traditional views of the coupling process. Understanding how energy from the solar wind gets coupled and transferred into the magnetosphere is a key component of space weather research, as it has implications for how and when geomagnetic storm and substorm activity can arise, the global magnetospheric convection process and how the radiation belts evolve, how aurora are driven, how energetic particles are produced, etc. Therefore, the development of solar wind-magnetospheric coupling models with increasing accuracy is critical for developing a quantitative and predictive understanding of space weather processes.

While early work on the subject used simple physical models to explain the coupling, efforts in recent times have furthered a quantitative link through the use of empirical modeling. The advantage of empirical modeling it that it is relatively straight-forward; the drawback is that the connection to the underlying physics is lost, which hampers the ability to increase the accuracy of the models and to determine how changes in solar wind parameters impact the subsequent coupling to the magnetosphere.

Recent developments by *Borovsky* (2008) have reawakened interest in the development of a first principles, physics based model of solar wind-magnetospheric coupling. The key departure of this new work relative to previous work is that it is argued that the coupling is proportional to the efficiency of the magnetic reconnection process that occurs when the interplanetary magnetic field meets the terrestrial magnetic field. Previous work assumed that the convective electric field in the solar wind (or some function of it) was the sole driver of the coupling. Borovsky's analysis, even in preliminary form, is finding as good a predictive capability as the best previously obtained empirical modeling.

These developments lead to a clear conclusion - the time is ripe for a multi-pronged and interdisciplinary revisitation to the problem of solar wind-magnetospheric coupling with the goal of resolving what controls solar wind-magnetospheric coupling and how one can develop quantitative predictions which will be of use to space weather applications. In particular, advancing our understanding will require efforts in observational and theoretical/numerical space physics. The purpose of this white paper is to recommend renewed systemic support for research on solar wind-magnetospheric coupling.

The impact of sustained decade-long inquiry into this topic will be an enhancement in our fundamental understanding of space physics and an increased ability to predict geomagnetic activity for applications to space weather phenomena. This has been a long term goal of space research, as summarized in "The Sun to the Earth -- and Beyond: A Decadal Research Strategy in Solar and Space Physics," the 2003 decadal survey from the National Research Council. Extending and expanding this goal for the next decade is justified because of the exciting new developments in the field.

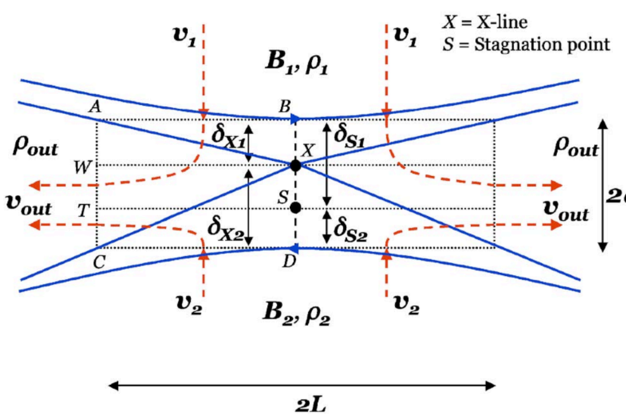
Recent Developments in Solar Wind-Magnetospheric Coupling Observations

It has long been considered the case that the efficiency of solar wind-magnetospheric coupling is a function only of parameters in the upstream solar wind. In particular, the Akasofu epsilon coupling function (*Perrault and Akasofu*, 1978) relates the coupling to the convective electric field in the solar wind. The correlation with observational data was good but had much room for improvement [see *Newell et al.*, (2007) for a review]. Since then, the modifications to the epsilon function have been suggested and tested in an effort to improve the correlation with observations. More recently, sophisticated multi-parameter fitting techniques have been used to achieve high levels of correlation between data and assumed functional forms of solar wind parameters. Such efforts have led to vast improvements in the obtainable correlation, nearing 75%.

Recent observations, however, provided motivation to rethink this paradigm. When the convective electric field in the solar wind increases abruptly, the enhanced coupling at the dayside magnetopause induces an upflow of plasma from the lower altitudes around the Earth. These so-called "plasmaspheric drainage plumes" (*Borovsky and Steinberg*, 2006) consist of relatively cold and dense plasma. When this plasma reaches the site of reconnection, the efficiency of solar wind-magnetospheric coupling is observed to decrease (*Borovsky and Denton*, 2006). This provides a very clear indication that the parameters in the solar wind are not solely responsible for the coupling. Therefore, complete models must take into account the parameters locally at the magnetopause, specifically those at the reconnection sites where the loading of solar wind energy to the magnetosphere is allowed to take place.

Recent Developments in Reconnection Theory

Spurred by the observations, interest in magnetic reconnection in magnetopause configurations substantially increased. The main deficiency in the understanding of reconnection in these settings was that the canonical models of magnetic reconnection by Sweet and Parker and by Petschekassume identical plasmas on either side of the dissipation region where the magnetic topology changes, but reconnection at the magnetopause is asymmetric, meaning that the magnetic field strengths and plasma densities are different on the magnetosheath and magnetospheric sides (*e.g.*, *Phan and Paschmann*, 1996). See the figure to the right as an example. There had been many studies on the effect of the asymmetry on the downstream shock structure, but it was not known how the efficiency of reconnection (the reconnection rate) changes due to the asymmetry.



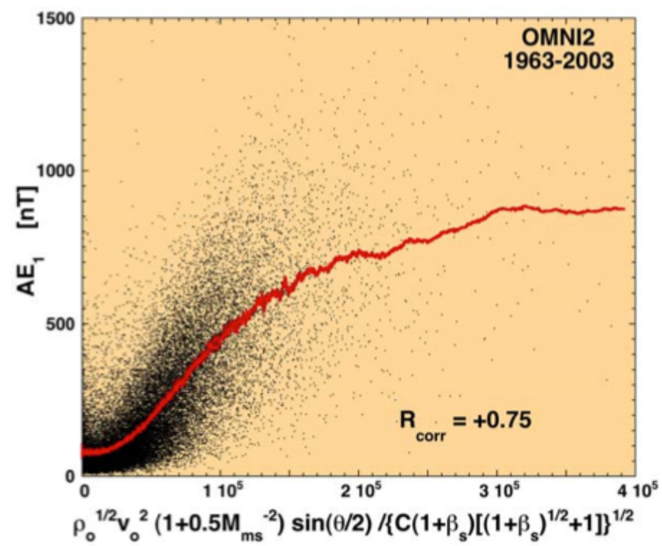
Schematic diagram of the dissipation region during asymmetric reconnection, reprinted from *Cassak and Shay* (2007).

Borovsky and Hesse (2007) performed numerical simulations of reconnection with different densities on either side to determine how the reconnection rate changed, finding that the main effect was that the effective Alfven speed of the process is based on a combination of the densities on either side. A first principles scaling analysis, which like the original Sweet-Parker analysis is based on conservation laws, was derived while including asymmetries in both magnetic field and density (*Cassak and Shay*, 2007). The derived expression for the reconnection rate was consistent with the findings of *Borovsky and Hesse* (2007). Since, it has been tested further and verified with two-dimensional simulations in resistive magnetohydrodynamics (*Cassak and Shay*, 2007), magnetohydrodynamics with localized resistivity (*Birn et al.*, 2008), Hall magnetohydrodynamics (*Cassak and Shay*, 2008), and particle-in-cell (*Malakit et al.*, 2010). Good agreement was also found in three-dimensional global magnetospheric simulations using magnetohydrodynamics (*Borovsky et al.*, 2008). Recent observations of reconnection at the subsolar magnetopause with the Polar satellite are shown to agree well with the predicted scaling (*Mozer and Hull*, 2010).

These studies have also uncovered other new aspects of reconnection. As a result of the upstream asymmetries, the dissipation region develops a different substructure than in symmetric reconnection. The X-line and the stagnation point are co-located in symmetric reconnection, but are separated in asymmetric reconnection (*Cassak and Shay*, 2007). This separation is borne out in the fluid simulations discussed above, as well as in more realistic particle-in-cell simulations (*Pritchett*, 2008; *Pritchett and Mozer*, 2009), though details of the model are remain under scrutiny (*Cassak and Shay*, 2009; *Birn et al.*, 2010; *Malakit et al.*, 2010). Recent particle-in-cell simulations have been profitably applied to direct observations of reconnection at the magnetopause, showing many aspects that are seen in the observations (*Tanaka et al.*, 2008; *Mozer et al.*, 2008a; *Mozer et al.*, 2008b). Also, recent studies employed the results and the analytical technique in studying magnetic reconnection in turbulent plasmas (*Servidio et al.*, 2009) and reconnection with asymmetries in the outflow direction (*Murphy et al.*, 2010).

Recent Developments in Solar Wind-Magnetospheric Coupling Functions

The development of a first principles prediction for the reconnection rate allowed *Borovsky* (2008) to develop a coupling parameter for solar wind-magnetospheric coupling which was predicated on local reconnection physics determining the efficiency rather than solely the properties of the solar wind. The so-called Borovsky coupling function was derived using pressure balance arguments to relate local reconnection site parameters to those in upstream in the solar wind. The prediction was compared with observational data, and it was concluded that the correlation was nearly 75%, as is shown in the plot to the right. Thus, the first-generation attempt to incorporate local reconnection physics provided as good a correlation with the data as the best previously obtained coupling functions which were obtained using unphysical empirical fitting techniques. Since then, independent studies have tested the coupling function, finding good agreement as well (*Turner et al.*, 2008).



Time lagged auroral-electrojet index AE as a function of the Borovsky coupling function in the black dots; a running average of the black points is plotted in red. Reprinted from *Borovsky* (2008).

The positive results are encouraging, but are clearly not the end of the story. The asymmetric reconnection theory on which the coupling function is based is purely a two-dimensional theory (as with the original Sweet-Parker model), but reconnection at the dayside magnetopause can be manifestly three-dimensional (*Dorelli*, 2008). *Borovsky* (2008) made assumptions about how the expression could be generalized, but these assumptions would benefit from further verification. Indeed, a recent study (*Ouellette et al.*, 2010) tested the two-dimensional reconnection theory against global magnetospheric simulations, finding good but not great agreement, though they also found that the agreement improved as the resolution was increased. Further, in global simulations with a southward directed interplanetary magnetic field, it was shown that for large enough interplanetary magnetic field strengths, the geoeffectiveness is not proportional to the field because the field convects around the magnetosphere instead of being reconnected (*Lopez et al.*, 2010), an effect which was not incorporated into the model.

Proposed Action

Due to the recent developments about the nature of solar wind-magnetospheric coupling and the prospective ability to develop increasingly accurate predictions, the coming decade provides a perfect opportunity for a careful and sustained effort on this topic. This should involve a multifaceted approach.

Theory and simulations of the fundamental physics of magnetic reconnection -

1) Improved theoretical understanding of how reconnection works at the magnetopause - there remain open questions about the properties of asymmetric reconnection, especially the substructure of the diffusion region and the impact of the substructure on observations. What other aspects play an important role? In many locations on the dayside magnetopause, the convection of the solar wind introduces a shear flow - how does this alter the efficiency of reconnection? How prevalent are other ion species, especially for reconnection near the cusps? Does this alter the reconnection?

   These studies can be carried out using two-dimensional magnetohydrodynamic, Hall-magnetohydrodynamic, hybrid, and particle-in-cell simulations.

2) Application of the two-dimensional models to the magnetosphere - There has been some work on whether the two-dimensional models are applicable to the magnetosphere, but a more complete determination is necessary. In particular, is the extension to the two-dimensional model employed by *Borovsky* (2008) appropriate for the magnetosphere? If not, is there a simple way to extend the two-dimensional model to incorporate such effects? If not, can one develop a first principles understanding of the efficiency of three-dimensional magnetic reconnection in the dayside geometry? Can the effects of a large convective electric field be incorporated into the model?

   These studies can be carried out using idealized two- and three-dimensional magnetohydrodynamic, Hall-magnetohydrodynamic, hybrid, and particle-in-cell simulations, as well as using global magnetospheric simulations. The latter are readily available to the scientific community at large through NASA's Community Coordinated Modeling Center operated at Goddard Space Flight Center.

Theory and analysis of solar wind-magnetospheric coupling -

1) Development of increasingly accurate coupling functions - as the understanding of fundamental reconnection physics improves, can the coupling function based on local reconnection physics can be enhanced? If so, do the advanced coupling functions give better correlations with the data?

2) Empirical studies of coupling functions - the previous empirical work chose a small number of parameters and particular functional forms that were used in fits to the data. Can empirical models be improved using the forms resembling Borovsky's coupling function? If so, can the improved fits feed back to the theoretical side and provide clues about what physics should be incorporated into the coupling function?

Satellite observations and data analysis -

1) Solar wind-magnetospheric coupling - Dayside reconnection is only the gateway to solar-wind/magnetosphere coupling: it magnetically connects the solar wind to the magnetosphere-ionosphere system. The coupling physics happens post-reconnection, with the reconnection rate controlling the amount of coupling. The physical processes that couple the MHD generator of the shocked solar wind to the magnetosphere and ionosphere have yet to be studied in earnest. Global MHD simulations, archival spacecraft and ground-based measurements, and new focused space missions should be marshaled upon this fundamental space-physics problem.

2) Properties of magnetic reconnection at the dayside magnetopause - Having more measured events of magnetic reconnection at the dayside is important for comparisons to simulations. In addition to present satellites such as Cluster and THEMIS/ARTEMIS, unprecedented spatial resolution of reconnection sites will be available from the Magnetic Multi-Scale (MMS) mission. A goal of MMS is resolving electron physics as it passes through reconnection diffusion regions. Such information will be invaluable for verification of simulations and theories of reconnection.

3) Identifying physics left out of models - The present coupling function has a 75% correlation with the data. By looking at the physical circumstances of the data that does not fit well with the model, can one ascertain key physical processes that are present in the real system that are not modeled well by the equations?

In summary, the topic of solar wind-magnetospheric coupling predictions is important with very high scientific value and has important implications for society at large. The activities are low risk and have a high level of technical readiness as much can be addressed using existing satellites and computational infrastructure.

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A National Ground Magnetometer Program for Heliophysics Research

A white paper for the 2013-2022 Heliophysics Decadal Study by the U.S. Space Studies Board

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Summary

Ground magnetic observations have become a network science made possible by multiple magnetometer projects. We recommend the establishment of a national ground magnetometer program to help coordinate, maintain, and enhance the magnetometer networks in North America and to support RBSP, MMS, and other Heliophysics missions in the next decade.

1. Background

As one of the most versatile scientific sensors for Heliophysics research, ground magnetometers make observations useful for generating geomagnetic indices such as Kp, Dst, and AE, estimating large-scale convection using the AMIE technique, and measuring various currents in the magnetosphere. Many of these functions can be fulfilled by magnetic measurements at a rate of one sample per minute, a time resolution provided by many geomagnetic observatories with decades of history. Nowadays all ground magnetometers established for Heliophysics research make measurements at a cadence of approximately one sample per second, enabling studies of the Ultra-low-frequency (ULF) waves (f = 1 mHz – 1 Hz) at a global scale to help diagnose the state of the magnetosphere.

In the last decade the high-cadence observations by ground magnetometer arrays brought in new Heliophysics science, and we witnessed a renaissance of ground magnetometers in the United States and abroad. Among the many research topics being studied using these new data, two topics have been the focal points of research to many magnetometer teams: (1) remote sensing of the magnetosphere using magnetoseismic techniques, and (2) observations of ULF power as a contributing factor of radiation belt dynamics. In the following we describe what enhancements in ground magnetic observations are required to conduct new research in these areas, and we explain why it is time to establish a national ground magnetometer program to help achieve the research objectives.

2. Magnetoseismic Research

For about a decade magnetoseismic research has been one of the major driving forces behind the development of new regional magnetometer arrays. It is now understood that magnetoseismology consists of both normal-mode and travel-time techniques [*1*]. When using ground magnetometer observations, the normal-mode magnetoseismic analysis identifies field line resonance (FLR) frequencies through the gradient method and infers the plasma mass density in the magnetosphere [*2,3*]. This technique has become mature in the last decade after it was used by a series of studies to examine the distribution of magnetospheric plasma, the plasmapause location, and the comparison with *in situ* measurements or images taken by satellites [*4-8*].

As opposed to satellite observations, ground magnetometer observations are well suited to the normal-mode analysis for studying the density variations at short time scales, such as those associated with the plasmaspheric dynamics during magnetic storms. Recent observations with normal-mode magnetoseismic analysis have demonstrated that the temporal variation of storm-time plasmasphere is well correlated with the variation of the ionospheric content, suggesting a strong coupling effect between the two regions at a time scale as short as a few hours [*6,9*]. The ionospheric influence on the plasmasphere during storme times remains an open question that requires more detailed comparison between observations and modeling results.

A recent technical advance in normal-mode analysis has revealed greater observational capability possessed by a two-dimensional network of ground magnetometers. Figure 1a shows an example of the normal-mode analysis using a single chain of magnetometers. As the chain slowly moves through different local times and observes the same set of flux tubes, the FLR-inferred equatorial densities present a smooth density variation in the L-LT (*L*-value and local time) plane. A two dimensional network, on the other hand, can allow station pairs that straddle two time zones to detect FLR frequencies, taking "snapshots" of equatorial density as demonstrated in Figure 1b. The red lines in the map of Figure 1b indicate the station pairs for which FLR frequencies can be successfully detected by using the gradient technique. Several regions in North America still lack ground magnetometers to form station pairs, and we have estimated that adding 30 new stations to the existing ~70 stations can provide the complete spatial coverage. From past experience this FLR technique works during the daytime and a few hours in the nighttime as well. In the future the enhanced ground magnetometer network in North America consisting of approximately 100 stations in total can be a powerful tool to monitor the spatial and temporal variations of the equatorial density in the magnetosphere.

Similar to terrestrial seismology for finding the time and location of earthquakes, travel-time analysis is another branch in magnetoseismology that can infer the start time and location of an impulsive signal. It is a relatively new topic, and initial successes have been obtained for detecting the plasmapause location [*1*] and the substorm onset in the magnetotail [*10*]. The travel-time analysis does not require ground stations to be closely spaced, but more ground stations are needed to reduce the uncertainty in inversion calculations. Travel-time magnetoseismology can potentially make ground magnetometers act in a way like seismometers for earthquakes, monitoring space weather events such as sudden impulses and substorms. This objective can be reached in the next decade by more research combining ground-based and spacecraft observations, numerical modeling, and travel-time inversion analysis. The ground-based magnetoseismic observations can also support the MMS mission to be launched in 2014, especially for the *in situ* observations by the four spacecraft of reconnection and other impulsive events in the nightside magnetosphere.

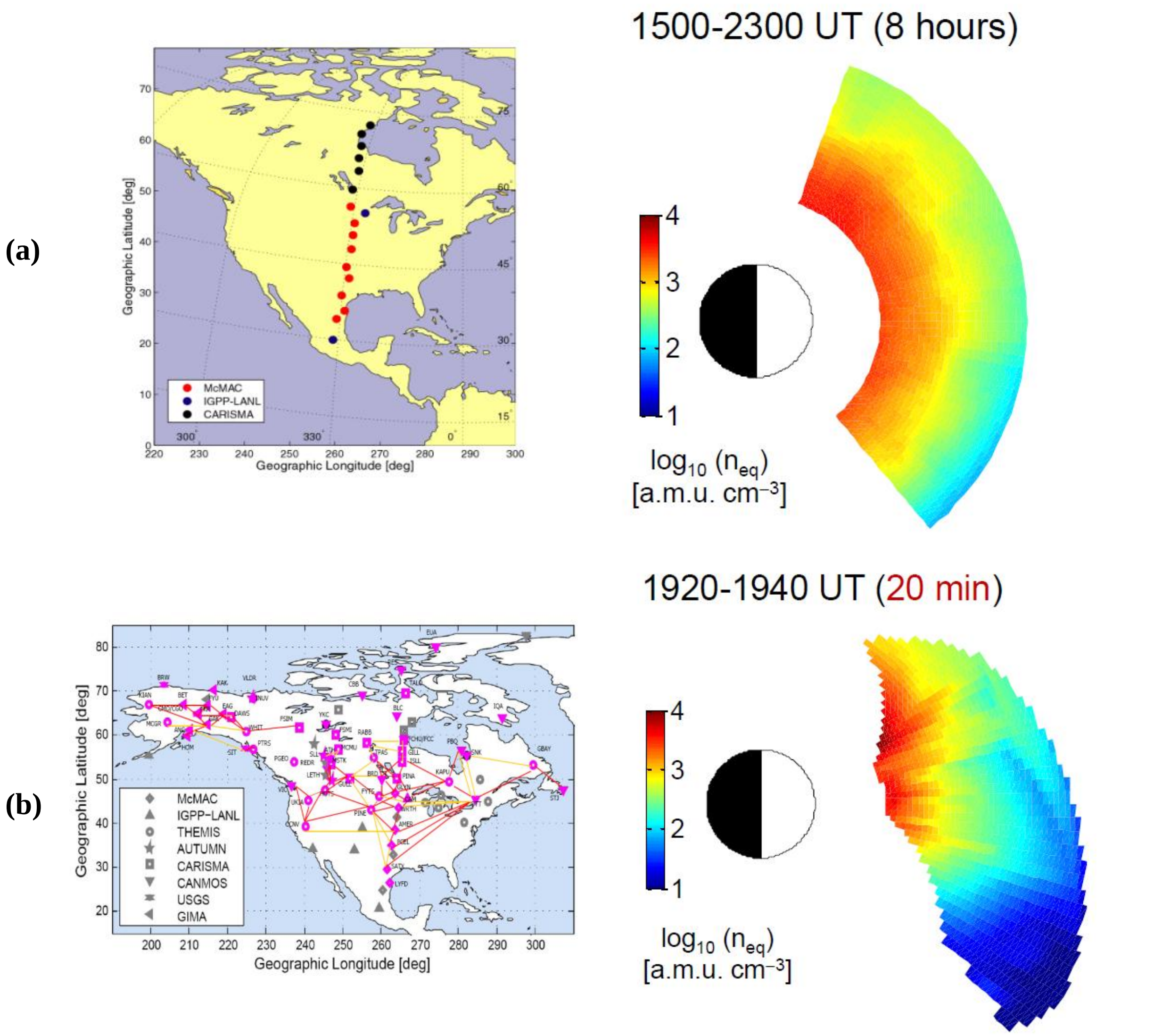

Figure 1. (a) Equatorial plasma density inferred from eight hours of observations by a chain of magnetometer stations. (b) A similar snapshot of equatorial density obtained by 20 minutes of data from a two-dimensional magnetometer array. Red lines indicate the station pairs useful for normal-mode analysis.

3. ULF Observations for Radiation Belts Research

In recent years ULF waves have received additional interest owing to their relationship to radiation belt dynamics. Observations have shown strong indication for acceleration of energetic particles to relativistic energies by Pc 5 wave action [*11*]. In theory wave cycles of Pc5 are commensurate with the drift periods of energetic electrons in the outer zone radiation belt, thus possibly violating the third adiabatic invariant and inducing particle transport. Global analysis of the wave structure in MHD simulations also finds that particles could interact with global, low-*m* toroidal mode waves through a drift-resonant interaction [*12*].

There have been several efforts devoted to the construction of ULF indices to aid the study of radiation belt dynamics, and such ULF indices have been found to be well correlated with the relativistic electron flux at geosynchronous orbit [*13*]. Nevertheless, Pc5 waves during storm times can vary significantly with locations [*14*], and numerical calculations have shown that the localized wave energy can be a significant factor in wave-particle interaction [*15*]. Further research should investigate the distribution of ULF waves as observed by widely distributed magnetometer stations to examine how the ULF waves influence radiation belt dynamics.

As the NASA RBSP Mission is expected to launch in May 2012, the timing for ground-based observations of ULF waves is critical. The existing magnetometer stations may have sufficient location coverage, but they need to continue the operation in order to provide timely ground observations of ULF waves during the RBSP Mission and the peak years of Solar Cycle 24.

4. Current State of Ground-based Magnetic Observations

Figure 2 shows the locations of fluxgate magnetometer stations that are currently operating or were once active in the last decade. With a goal different from measuring the accurate baseline of the geomagnetic field at a low cadence, these stations sample vector magnetic field every 5 seconds or shorter, aiming primarily at Heliophysics observations.

It is clear from the map that a magnetometer network in North America can have the best coverage in *L*-values. Currently there are approximately nine magnetometer arrays with more than 70 stations operating in North America, each focusing on the measurements in one region or one time zone. As discussed earlier the station coverage in some areas of the continent is still insufficient for making 2-D snapshots of magnetospheric density, and the FLR analysis can easily make recommendations on the locations of additional magnetometer stations.

In fact a more serious issue with the present magnetometer network is the risk that many existing stations may face closure sometime in the next decade. This problem is germane to the nature of the funding process in the United States, for which each project lasts for only 3-5 years. The expense to cover the running costs of ground magnetometers and continue their operation is miniscule in comparison with the operation of a space mission, but without such a small investment the magnetometers available today can disappear tomorrow. Continuous magnetometer observations for at least one solar cycle require a consistent maintenance program that can go beyond the horizon of a regular research grant.

Another challenge for modern magnetometer observations is related to the fact that **ground magnetometer observations have become a network science**, and therefore close collaboration among individual magnetometer projects and data services is more than ever critical in providing the network observations to the whole community. Gone are the days when new science can be expected by having the observations from a handful of magnetometer stations. Scientists today demand multiple years of ground magnetometer observations over a wide region to conduct their Heliophysics research. Examples are the studies on normal-mode magnetoseismology and on ULF waves for radiation belts, both requiring network observations made by multiple magnetometer arrays. From past experience and the long-time observation of domestic and foreign magnetometer projects, an average-size magnetometer team with several members can run up to 10 stations, and having much more stations is logistically difficult and can reduce the quality of local support that each station deserves. The future of ground magnetometer observations for Heliophysics research depends on if multiple magnetometer teams can provide sufficient observational coverage consistently and how they as a whole provide network observations to the community.

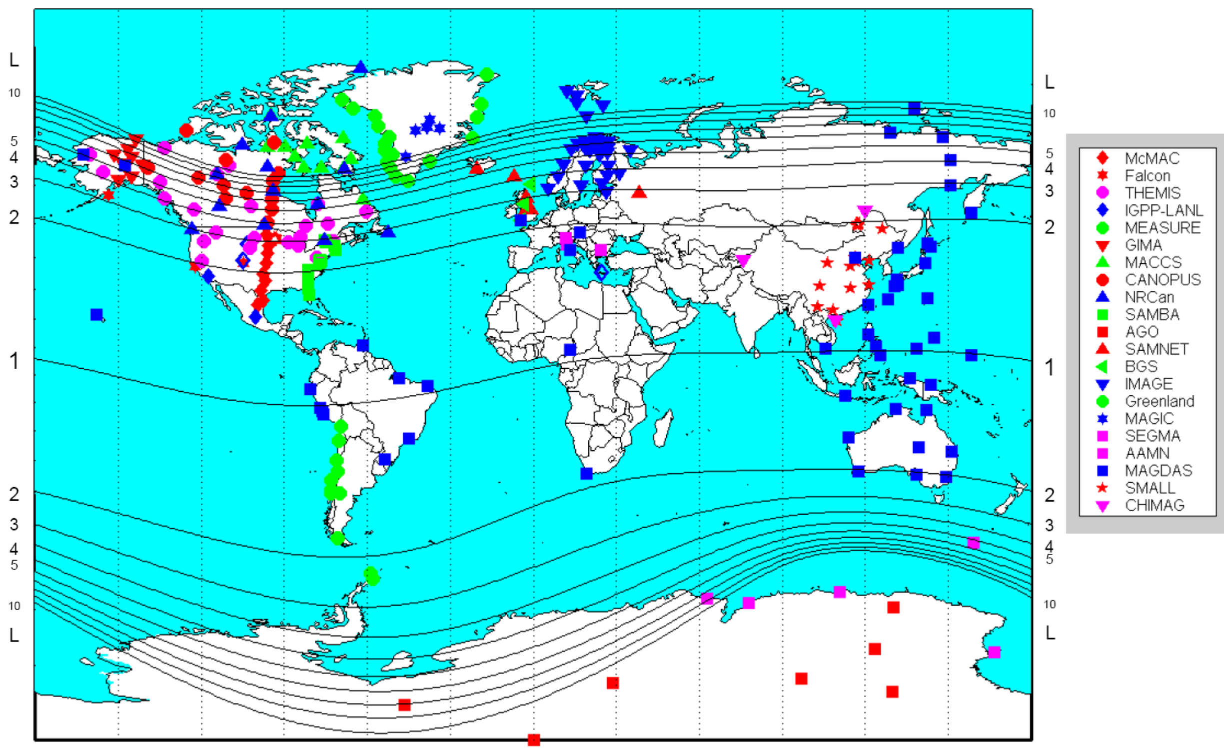

Figure 2. A world map of high-cadence (5-second a sample or better) geomagnetic observations for Heliophysics research in the last decade [*16*]. Some recently built stations are not included in this map.

5. Recommendations

We recommend maintaining and enhancing existing ground magnetometer networks in order to support new research in magnetoseismology and in the ULF waves for radiation belt dynamics in the next decade. In particular, we recommend **improving the present magnetometer arrays in North America to form a dense 2-D network** that can enable monitoring the distribution of plasma density in the magnetosphere. These ground-based magnetic observations also need to be consistent through the next decade in order to provide adequate support to future Heliophysics missions such as RBSP and MMS.

To help reach the above objective, we recommend **the establishment of a "national magnetometer observatory" for Heliophysics research** – a national program that supports and coordinates multiple ground magnetometer projects and the data service projects. Analogies in other fields include the various AURA centers for astronomy [*17*] and IRIS for Earth science [*18*], and the ground magnetometer program can be tailored to meet the needs by the Heliophysics community. There are approximately 10 U.S.-funded magnetometer projects making observations domestically or abroad, in addition to several data service projects serving ground magnetometer data through either online archives or virtual observatories. The existence of a national program has many advantages in steering these activities performed by multiple parties so that the network observations by ground magnetometers can be provided in an efficient fashion. A national program can facilitate the standardization in several key aspects of the infrastructure, such as measurements, data format, and data dissemination, and reduce the inefficiency due to the different ways in operation. A national program can attract colleges and high schools to participate in ground magnetometer observations and provide them with the educational resources at the national level. The powerful network of ground magnetometer observations coordinated by the U.S. national program can bring in further collaborative opportunities with international magnetometer teams through which joint magnetometer observations across the globe can be made available.

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[17] Association of Universities for Research in Astronomy (AURA, http://www.aura-astronomy.org/) is a consortium that operates world-class astronomical observatories termed "centers." One of the AURA centers is the National Solar Observatory that coordinates multiple solar observing facilities and projects in the nation.
[18] Incorporated Research Institutions for Seismology (IRIS, http://www.iris.edu/hq/) is a university consortium sponsored by the National Science Foundation that is dedicated to the operation of scientific facilities for the acquisition, management, and distribution of freely available seismic data.

Heliophysics Instrument and Technology Development Program (HITDP)

A white paper for the 2010 Solar and Space Physics Decadal Survey

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Introduction

This white paper will put forth the case for a dedicated Heliophysics Instrument and Technology Development Program (HITDP). Given the potential commonality in the required tools and methods across Heliophysics sub-disciplines, this program would be implemented as a single separate program element under the Research Opportunities in Space and Earth Science (ROSES) solicitation. Having a HITDP will re-invigorate hardware development in the Heliophysics community, provide a pathway for new technology to be infused into sub-orbital, Explorer, and larger missions, help develop the next generation of Heliophysics instrument scientists, and help ensure a healthy science mission program for many years to come. HITDP will be invaluable for increasing the Technical Readiness Level (TRL) level of instruments prior to when they are proposed for missions, thus decreasing mission risk, which decreases cost and, in the long run, pays for the program.

This white paper is applicable to all three Decadal Survey study panels.

Discussion

In NASA's Science Mission Directorate (SMD), the Heliophysics Division is the **only** science division that lacks any separate instrument development program as part of the Research Opportunities in Space and Earth Sciences (ROSES). The Astrophysics Division has the Strategic Astrophysics Technology Program (SAT), Planetary Science has the Astrobiology Science and Technology for Instrument Development (ASTID), the Planetary Instrument

Definition and Development Program (PIDDP), the Mars Instrument Development Project (MIDP), and the Mars Technology Program (MTP). The Earth Science Division has an Instrument Incubator Program and an Advanced Component Technology program. Because the Heliophysics Division does not always break out instrument development spending separately it is a little difficult to determine, but it appears that the Heliophysics Division has the lowest ratio of instrument development funding to total budget in SMD.

Heliophysics has a Low Cost Access to Space (LCAS) segment of its R&A program, but this is for higher TRL instruments that are ready for large-scale sub-orbital missions. And there are instruments, especially in heliospheric science, that cannot be tested with sub-orbital because they need very pure vacuum and require outgassing time. Instruments at a low TRL can apply to the Supporting Research and Technology Program in either Geospace (GEO), or Solar and Heliospheric (S&H) science. The Geospace program calls out Instrument Development as a separate funding portion of the SR&T program, and S&H mentions it, but lumps the funding in with all other research. One of the many issues with the current system is that many instruments, such as those that measure particles and fields, are useful in both GEO and S&H mission, but the current selection method forces a bifurcation that can be seen across too much of the community. Also, the Living With a Star Targeted Research and Technology rarely actually targets technology, leaving space weather instrumentation with few opportunities.

Over the last few decades, increased launch and mission costs have reduced the launch rate for SMD missions. This has reduced the number of places in the country that are capable of supporting a flight instrument development. The remaining hardware centers are fighting repeated battles to keep the right skill mix of technicians and engineers employed, as the low launch rate requires effort that is "bursty", with time periods that require a large amount of effort, but other times when work and funds can be lacking. Scientists are less affected by this problem because data analysis can help to smooth out this rough hardware funding profile. Even the locations that have been able to keep a steady flow of work are often only one-person-deep in some skills, which makes it harder to deal with problems that can occur, increases risk to the instrument delivery schedule, and all but eliminates the organizations' ability to infuse new talent into instrument and technology development. A dedicated instrument development program can assist by keeping skilled personnel at work, designing the next generation of instruments when flight projects are not at their peak work load. This would help to smooth the funding flow, support highly productive groups with the required skills, and provide needed opportunities for students to get involved in instrument development. In other words, such a program would provide triple benefit, by promoting innovative instrument development, providing crucially needed means to keep essential engineering talent during inevitable valleys between consecutive missions, and promoting the training of new engineering talent.

HITDP will reduce risk on flight missions, by enabling proposals for new instruments at a higher TRL. More early effort in the design, construction, and testing of instruments will clearly reduce risk in the flight development. HTIDP also allows for development of new technology that might be deemed as high risk and therefore un-proposable without this program. HITDP also decreases the risk and increases the effectiveness of the LCAS program. Delays in LCAS first launches are often due to emerging issue with the instrument development. It would be better to start the effort and incur the cost of a first sub-orbital flight only after the instrument is already designed and tested, thus allowing more sub-orbital opportunities.

Many of the Heliophysics flight instruments recently developed or currently under development are the result of incremental improvements over previous flight instruments. Indeed, there is often a complaint from outside of Heliophysics that a lot of what we propose to do scientifically comes down to just “more of the same”. The health and future of Heliophysics research requires that we constantly push the boundaries of what we can observe, and HITDP can help develop new instrumentation that will give us large jumps in measurement capability instead of just incremental improvements.

In addition, HITDP can be used to provide training for future experimentalists. With the few SMD flight programs these days, the number of knowledgeable experimentalists that are involved in hardware development have gradually decreased over time. In the current risk adverse environment, flight programs often cannot provide the right opportunity to teach the next generation experimentalist. HITDP can provide ample opportunity for the community to propose for low TRL instruments, which is a perfect training ground for the next generation experimentalists.

HITDP can also maintain the specialized test infrastructure that is needed for many Heliophysics instruments, such as accelerators, thermal-vacuum test chambers, etc.

Cost and Implementation

At the simplest level, the HITDP could be implemented just by combining the existing funding already set aside for instrument development in the current Heliophysics Geospace and Solar and Heliospheric SR&T programs into a separate ROSES element. The Geospace program has approximately $300K available for new Instrument Development grants in ROSES FY10, and if we assume three year grants and a roughly equivalent amount coming out of the Solar and Heliospheric SR&T program, that gives a $1.8 M program. But this is less than a third of a percent of the Heliophysics Division budget, is smaller than the amount spent on Data Environment improvements, and would only serve to maintain the status quo. Therefore, we recommend that this budget be increased to at least $1M per year of new HITDP grants and preferably more. In addition, co-funding with NASA’s new technology development infrastructure should be explored (NASA technologists have often seen Heliophysics as a poor place to invest, due to the lack of potential technology funding within the Heliophysics program). It is understood that this may be a “zero sum” exercise, and that there is probably no significant increase in the Heliophysics Division budget. However, it appears that the increased launch and mission costs have caused the budget to become unbalanced. Rather than decreasing the already reduced research budget, this new HITDP money needs to come out of the mission budget. Development and delivery of flight instruments is frequently an issue for mission costs. Having a robust HITDP will help reduce risks on the construction of flight instruments and, in the long run, pay for itself.

Conclusion

The Heliophysics Division has clearly been investing very little in technology development, and this puts the future of the field at risk. In order to maintain an active and innovative hardware development community, to reduce mission risk, and to develop the new instruments that will acquire the data that the community needs to further its science goals, Heliophysics should increase the percentage of its budget that goes to new instrument concepts. The easiest and most obvious way to do this is to formally designate a Heliophysics Instrument and Technology Development Program as a ROSES element. This will also help align the division with the other SMD science divisions, all of which have assigned a higher percentage of their budget to technology because they see the utility of instrument development.

Geospace Dynamics Imager: A Mission Concept for Heliospheric and Magnetospheric Imaging and Space Weather Forecasting

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Overview

The white-light imagers comprising the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI) on the twin Solar Terrestrial Relations Observatory (STEREO) spacecraft have recently demonstrated a new, groundbreaking capability to image the large-scale driving solar plasma structures, coronal mass ejections (CME) and co-rotating interaction regions (CIR), from the Sun to the Earth and the less structured solar wind from the Sun out to about one-third the Sun-Earth distance (Figure 1). This imaging capability allows us to track and model the three-dimensional propagation of CMEs and CIRs from the Sun to the Earth [*Wood et al.*, 2010]. The success of these imaging technologies in the vicinity of the Sun and in the heliospheric volume containing the Earth suggests that the next logical step in sensor technology development is to investigate the possibility of instruments capable of directly imaging the interface between the incident solar wind and the Earth's magnetosphere, and the response of the coupled magnetosphere-plasmasphere-ionosphere system to all incident solar plasmas.

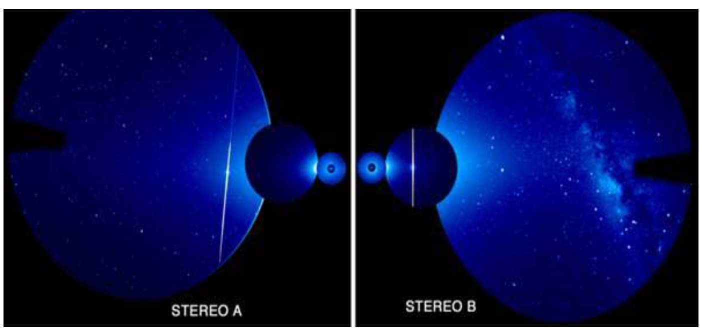

Figure 1. Panoramic SECCHI views of the heliosphere from the STEREO A and B spacecraft. White-light, Thomson scattering imaging has made it possible to directly observe the solar wind and the structures embedded within it. Shown at the center are the fields of view of the COR1 and COR2 coronagraphs on STEREO A (left) and B (right) which observe from 1.5 – 4.0 solar radii and 15 solar radii, respectively. The Heliospheric Imager 1 field of view begins near the outer portion of the COR2 field of view and extends outward from the Sun to about a third of the distance to Earth's orbit on both STEREO A and B. The large circular fields of view shown above are those of the Heliospheric Imager 2 instruments which extend the observations to Earth's orbit. Earth is hidden in the HI2 field of view by the trapezoidal shaped occulter in both panels.

In this white paper we describe the Geospace Dynamics Imager (GDI) mission concept which adapts current solar coronal and heliospheric imaging techniques to directly and globally observe the Earth's magnetosphere by observing Thomson scattering of solar visible light by geospace electrons. We will demonstrate that direct imaging of both the variable solar plasmas incident on the magnetosphere and the dynamic response of the extended magnetosphere, plasmasphere, and upper ionosphere to them is feasible. We will describe the path to achieving this capability by extending our experience and expertise with solar coronagraph and heliospheric imager technologies. Direct imaging of the Earth's magnetosphere seamlessly across its primary regions and its interface with the solar wind will enable major advances in our understanding of solar wind-magnetosphere interactions. The GDI mission concept will provide an unprecedented and unique global context for space weather research and applications, just as space-based global observations of the Earth's surface and lower atmosphere are an indispensible tool for assessment and forecasting tropospheric weather on both regional and global scales.

Motivation/Background

The ability to view a complex system in its entirety enables radical transformations of our first-principles understanding of the world and our ability to adapt to operating within it. The first images of global weather patterns broadcast by the Television Infrared Observation Satellite (TIROS-1) in the 1960s and the subsequent global imagery from the first Geostationary Operational Environmental Satellites (GOES) in the 1970s laid the foundation for modern tropospheric weather forecasting and climate research. More importantly, the ability to globally observe and monitor weather systems like hurricanes provides us with actionable information that allows forecasters to mitigate the effects of natural disasters (Figure 2, left). The foresight provided by global situational awareness saves lives and property. Another example of the transformative power of global imaging is the first glimpse of the Earth at far-ultraviolet wavelengths taken from the surface of the moon by the Apollo 16 Far-Ultraviolet Camera/Spectrograph [*Carruthers*, 1973] (Figure 2, right). These pioneering images revealed the global structure of both the dayside and nightside ionosphere and the hydrogen geocorona for the first time.

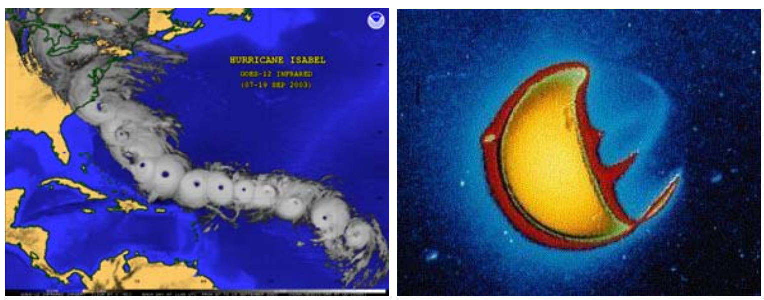

Figure 2. Examples of global imagery that revolutionized our understanding of complex, global systems. Left: GOES imagery of global weather patterns from geosynchronous orbit has enabled modern weather forecasting and natural disaster mitigation capabilities. Shown is a composite of GOES-12 infrared images of the track of Hurricane Isabel in September 2003 as it approached landfall on the east coast of the United States. Right: The first global, far-ultraviolet image of the Earth taken from the moon by the Apollo 16 Far-Ultraviolet Camera/Spectrograph provided a comprehensive and simultaneous view of both the dayside and nightside ionosphere.

The highly variable, out-flowing solar plasma drives the extent, shape, and state of the Earth's magnetosphere, plasmasphere, and ionosphere. Observation of this critical volume of space has been mostly accomplished thus far using highly localized, non-imaging in situ techniques. Early Earth imaging research, reviewed by *Williams et al.* [1992], targeted selected geospace regimes. The imaging methods employed thus far have utilized proxies of the total plasma density, such as radiative recombination emissions in the ionosphere, helium ion emission at 30.4 nm from the plasmasphere, or energetic neutral atoms (ENAs) from the ring current region. Most recently, the NASA Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite utilized such imaging systems to study the response of the inner magnetosphere to changing solar wind conditions [*Burch*, 2003; 2005]. More recently, *Collier et al.* [2010] proposed imaging the magnetopause region by observing soft x-rays produced by charge exchange between heavy ions in the solar wind and neutral atoms from the Earth's exosphere. While IMAGE and other missions have made significant progress in characterizing and understanding large scale processes in selected geospace regions, the global context afforded by imaging the electron density on a scale that includes all of geospace and its interface with the solar wind promises major advances in both our fundamental understanding of solar wind-magnetosphere coupling and our ability to forecast the state of the geospace environment in response to solar wind driving.

Meier et al. [2009] realized that the technical challenges associated with the optical detection of the faint magnetosphere surrounding the bright Earth are similar to those associated with imaging the faint corona surrounding the bright solar photosphere. In that study we examined the possibility of adapting demonstrated solar coronagraph methods for the detection of Thomson-scattered radiation near the Sun to global imaging of the Earth's dynamic magnetosphere. This was done by simulating Thomson scattering images of the Earth's magnetosphere taken by a hypothetical coronagraph-like instrument observing from various orbits. The Lyon-Fedder-Mobarry (LFM) 3-D MHD model [*Fedder and Lyon*, 1987] was used to specify electron densities in the magnetosphere while the SAMI3 model [*Huba et al.*, 2000] was used to set the plasmaspheric and ionospheric electron densities. The brightness of the Thomson scattered solar radiation from electrons in geospace was computed from these electron density distributions, allowing us to form images of what the magnetosphere, plasmasphere, and topside ionosphere would look like when observed by a white-light, "geo"-coronagraph. The details of this calculation are given in *Meier et al.* [2009] but in short, the Thomson scattering brightness is proportional to the line of sight column electron density. We assume the primary background noise sources to be the zodiacal light and the instrumental stray light diffracted around the occulter. Point sources such as stars are neglected for the time being.

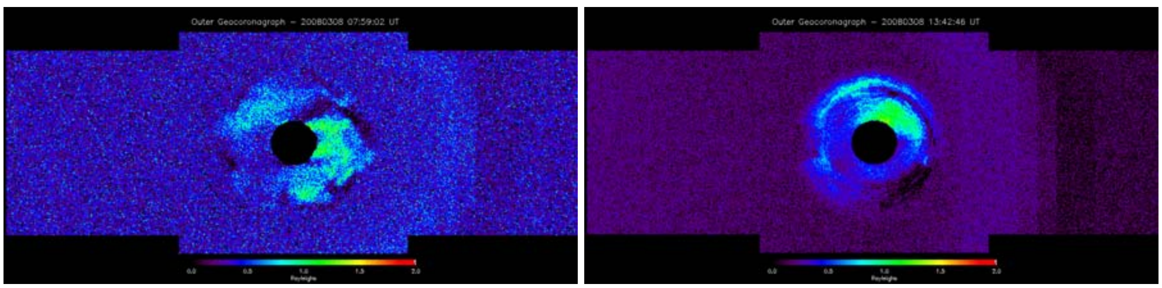

Figure 3. Simulated white-light, Thomson scattering images of the magnetosphere and plasmasphere as viewed from a coronagraph-like instrument in the equatorial plane (left) and looking down onto the equatorial plane from a polar perspective. The magnetospheric features that are observed in these images include the instantaneous locations of boundaries such as the bow shock, the magnetopause, and the plasmapause, the global morphology of the plasmasphere, and the magnetic cusps (left).

Figure 3 shows two examples of simulated white-light, Thomson scattering images of the magnetosphere from two perspectives. The scene background consisting of the zodiacal light and the diffracted stray light are subtracted to yield the magnetospheric Thomson scattering signal. The left panel shows a simulated view of the magnetosphere from an observer in the equatorial plane while the right panel shows the equatorial plane of the magnetosphere (X_{GSE}-Y_{GSE} plane) from an observer looking down from a polar orbit. In both cases the Sun is oriented to the right of the images and the solar wind propagates from right to left. The central, square field of view in each image is assumed to be that of a coronagraph-like instrument which focuses on the inner magnetosphere out to about 6.0 R_E. The disk of the Earth is occulted in each example by an assumed external occulter with an inner field of view cut-off of 1.2 R_E. The two squares to each side are assumed to be the fields of view of a Heliospheric Imager (HI)-like instrument designed to view the magnetopause and magnetotail regions. Instrumental noise is included in these image simulations. The zodiacal light background and instrumental stray light background are subtracted from these images. The instantaneous position and morphology of the bow shock, magnetopause, and the magnetosheath are observable over a wide range of local times. The global plasmapause position and plasmaspheric morphology are also readily visible in these images. Smaller scale features like the northern magnetic cusp structure can also be discerned (Figure 3, left). In our simulation we assumed individual image frames would be collected at a cadence of about one-minute and co-added to form images with integration times ranging from 10-15 minutes to improve the signal to noise ratio. Given the range of assumptions for the orbit (30 R_E to lunar orbit), detector field of view (23°), and detector size (10240×10240 binned down to 320×320) used in these image simulations we expect to achieve spatial resolutions on the order of 250-500 km.

Expected Impact of Geospace Dynamics Imager Mission

The Geospace Dynamics Imager mission will facilitate a true leap forward in our understanding of the physical processes involved in solar wind-magnetosphere coupling and in our ability to develop and verify space weather forecasting capabilities that will find wide usage in the military and civilian communities. Global images of geospace would reveal the near-instantaneous morphology of magnetospheric boundaries and allow us to greatly advance our fundamental understanding of solar wind plasma transport into the magnetosphere. The GDI mission will improve our specification of boundary dynamics in the inner magnetosphere by showing the instantaneous location of the plasmapause at all local times. This will provide a better understanding of plasmaspheric erosion and re-filling during geomagnetic storms. Since the plasmasphere is directly coupled via magnetic field lines to the ionosphere, images revealing the dynamics of the plasmasphere would also yield the upper boundary conditions for ionospheric specification. Current efforts to specify and to eventually forecast the state of the ionosphere could heavily leverage this new imaging capability to extend both the spatial domain of existing space weather models and the time window for which forecasts could be produced.

Applications and operational fields that will likely be impacted by Geospace Dynamics Imager observations include the improvement of space situational awareness (SSA) and anomaly resolution, the forecasting of satellite environments, assessment of communication capabilities, and potentially improving accuracies and mitigating outages of Global Positioning System (GPS) navigation assets. The availability of geospace electron density distribution data will facilitate the development of next generation, physics-based assimilation models that have a high potential of significantly improving the currently available forecasting capabilities.

The Geospace Dynamics Imager mission addresses the themes of all three NRC Decadal Survey study panels by:

- Enabling seamless tracking of solar wind disturbances from the heliosphere to the Earth’s magnetosphere. *Chua et al.* [2009] demonstrated this capability by combining STEREO SECCHI data with simulated white-light Thomson scattering images of the geospace to show how a CIR could be tracked from the Sun to the Earth and how its impact on the Earth’s magnetosphere could be imaged.
- Determining how electrons in the magnetosphere, plasmasphere, and ionosphere are redistributed in response to solar wind forcing, particularly when CMEs and CIRs interact with geospace.
- Improving our understanding of mechanisms that transport solar wind plasma into the magnetosphere such as the Kelvin-Helmholtz instability at the magnetopause and flux transfer events.
- Observing variations in the plasmaspheric boundaries and improve our understanding of how the plasmasphere is coupled to the global dynamics of the magnetosphere and the ionosphere.
- Establishing the sensitivity of space weather forecasts to initial conditions in the magnetosphere and provide global boundary conditions to geospace specification models.

Technical Approach

The concepts, simulations, and analysis developed by *Meier et al.* [2009] and *Englert et al.* [2009] enabled us to conclude that it is feasible to use white-light, Thomson scattering imaging to globally image the Earth’s magnetosphere, plasmasphere, upper ionosphere, and their dynamic interactions with the solar wind with small to medium-class satellite sensor systems. The Geospace Dynamics Imager would be comprised of a pair of white-light imagers:

Solar Plasma Imager (SPI): The SPI would be an evolution of the STEREO SECCHI Heliospheric Imager (HI) design that would leverage new large-format focal plane array (FPA) detectors to increase the signal to noise ratio by an order of magnitude and the light gathering power by two orders of magnitude. This increase in light gathering power will allow the background solar wind to be imaged at large elongations from the Sun in addition to the brighter (i.e. higher density) CME and CIR structures. The SPI would observe the region of interplanetary space just upstream of the Earth's magnetopause region to image the solar wind incident on the magnetosphere.

Figure 4. The Solar Plasma Imager (SPI) is a next-generation heliospheric imager that would couple wide-field optics with a large-format focal plane array to provide orders of magnitude increase in light gathering power over current heliospheric imagers.

Geocoronagraph: The Geocoronagraph would be an adaptation of a solar coronagraph optimized for direct observation of the Earth's magnetosphere and plasmasphere and the response of geospace to solar wind forcing. The field of view of the Geocoronagraph would be centered on the Earth and would extend out to include the plasmasphere and magnetopause boundary regions. The bright disk of the Earth would be blocked by an external occulter with an inner field of view cut off between 1.2 – 2.0 Earth radii.

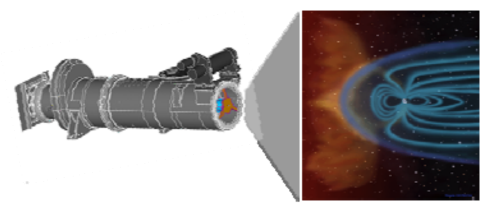

Figure 5. The Geocoronagraph is an adaptation of a solar coronagraph optimized for viewing the Earth's magnetosphere.

The enabling technologies that would make the Solar Plasma Imager and the Geocoronagraph possible include: (1) next-generation external occulters and baffles that will be capable of attenuating diffracted stray light from the sunlit disk of the Earth by one to two orders of magnitude greater than existing designs and (2) large-format focal plane array detectors coupled to wide-field optics. The Geospace Dynamics Imager mission will leverage ongoing research for the design of the external occulters and baffle systems for the Compact Coronagraph (CCOR) and the Wide-field Imager for Solar Probe (WISPR). A number of large-format detectors with CCD arrays larger than 4096×4096 have been developed for recent missions like the Joint Milli-Arcsecond Pathfinder Survey (JMAPS) and Kepler. GDI will take advantage of these new large-format FPA detectors to enable to use of scaled-up optical systems to increase the light gathering power of the Solar Plasma Imager and Geocoronagraph by orders of magnitude relative to their predecessors. This will be necessary to detect the faint Thomson scattering signal in geospace against the bright zodiacal light background.

Possible orbits from which GDI would observe the heliosphere and geospace include lunar orbit, a highly eccentric polar orbit with an apogee near 30 R_E, or the L5 Lagrange point. A trade-space study to determine the optimal orbit from which to globally view the Earth's magnetosphere and its interface to the solar wind is necessary. Access to these high Earth orbits will most likely necessitate a dedicated spacecraft and an Evolved Expendable Launch Vehicle (EELV) like an Atlas V or a Delta IV, or a Falcon 9. One solution to mitigate the costs and difficulties of accessing an EELV launch as a dedicated mission is to configure the Solar Plasma Imager and the Geocoronagraph as primary payloads on an EELV Secondary Payload Adapter (ESPA) ring wherein the ESPA ring itself will be used as the satellite bus. NASA's Lunar CRater Observation and Sensing Satellite (LCROSS) mission was the first to successfully use this technique to access a high-altitude orbit at a relatively low cost. Either one ESPA ring could be used to house both the Solar Plasma Imager and the Geocoronagraph or each imager could be integrated into their own ESPA rings and flown separately if it is determined that optimum viewing will be achieved for each instrument from different orbits. In either case GDI could be manifested as a secondary payload on an EELV or Falcon 9.

Schedule and Cost Estimate

The estimated project phases and milestones for the Geospace Dynamics Imager mission over 10 years are summarized in Table 1.

Table 1. Estimated phases and milestones for 10-year Geospace Dynamics Imager mission.

Phase #	Phase/Milestone	Duration (Months)
1	Mission Concept Definition	12
2	**Phase A (Requirements definition)**	6
3	**Phase B (Preliminary design)**	10
	Instrument PDR	
	Mission/Spacecraft PDR	
4	**Phase C (Critical design)**	12
	Instrument CDR	
	Mission/Spacecraft CDR	
5	**Phase D (Instrument delivery to spacecraft)**	18
	Instrument TRR	
	Spacecraft integration and testing	8
7	**Launch processing**	3
	Launch date	
8	**Instrument Commissioning**	1
9	**Phase E (Mission Operations)**	60
10	**Phase F (Mission Closeout)**	2
	Total Investigation (Phases A – F)	120

The cost estimate developed for the Geospace Dynamics Imager mission over 10 years is shown in Table 2 in FY10 dollars. The cost estimate assumes a dedicated spacecraft with the Solar Plasma Imager and Geocoronagraph as the primary instrument payloads and a dedicated EELV-class launch vehicle. However, launch costs could be significantly reduced if GDI is manifested as a secondary payload using an ESPA ring as the spacecraft bus. The work breakdown structure (WBS) shown in Table 2 roughly follows the mission phase sequence given in Table 1.

Table 2. Estimated costs in FY10 dollars for a Geospace Dynamics Imager mission over 10 years.

WBS Name	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Totals
Program Management	$ 1,150,000	$ 1,050,000	$ 2,500,000	$ 3,000,000	$ 2,250,000	$ 1,000,000	$ 1,000,000	$ 650,000	$ 500,000	$ 200,000	$ 13,300,000
Instrument management	$ 400,000	$ 500,000	$ 750,000	$ 750,000	$ 750,000	$ 500,000	$ 500,000	$ 250,000	$ 250,000	$ 100,000	$ 4,750,000
Spacecraft bus management	$ 500,000	$ 50,000	$ 1,000,000	$ 1,500,000	$ 1,000,000	$ -	$ -	$ -	$ -	$ -	$ 4,050,000
Program support	$ 250,000	$ 500,000	$ 750,000	$ 750,000	$ 500,000	$ 500,000	$ 500,000	$ 400,000	$ 250,000	$ 100,000	$ 4,500,000
Systems Engineering/Mission Analysis	$ 600,000	$ 1,500,000	$ 1,500,000	$ 2,500,000	$ 2,000,000	$ 600,000	$ 500,000	$ 500,000	$ 100,000	$ -	$ 9,800,000
Project/Software Systems Engineering	$ 250,000	$ 500,000	$ 500,000	$ 750,000	$ 500,000	$ 500,000	$ 500,000	$ 500,000	$ 100,000	$ -	$ 4,100,000
Analysis	$ 250,000	$ 750,000	$ 750,000	$ 750,000	$ 500,000	$ 100,000	$ -	$ -	$ -	$ -	$ 3,100,000
Contamination/Materials/Reliability	$ 100,000	$ 250,000	$ 250,000	$ 1,000,000	$ 1,000,000	$ -	$ -	$ -	$ -	$ -	$ 2,600,000
Safety, Reliabilty, and Mission Assurance	$ 70,000	$ 250,000	$ 500,000	$ 500,000	$ 250,000	$ -	$ -	$ -	$ -	$ -	$ 1,570,000
Payload Development and Testing	$ 1,400,000	$ 5,750,000	$ 25,500,000	$ 6,250,000	$ 3,500,000	$ 250,000	$ 100,000	$ 50,000	$ 50,000	$ -	$ 42,850,000
Solar Plasma Imager (SPI)	$ 400,000	$ 1,500,000	$ 10,000,000	$ 1,500,000	$ 1,000,000	$ -	$ -	$ -	$ -	$ -	$ 14,400,000
Geocoronagraph	$ 400,000	$ 1,500,000	$ 10,000,000	$ 1,500,000	$ 1,000,000	$ -	$ -	$ -	$ -	$ -	$ 14,400,000
Instrument electronics	$ 500,000	$ 2,500,000	$ 5,000,000	$ 2,500,000	$ 1,000,000	$ -	$ -	$ -	$ -	$ -	$ 11,500,000
Instrument software	$ 100,000	$ 250,000	$ 500,000	$ 750,000	$ 500,000	$ 250,000	$ 100,000	$ 50,000	$ 50,000	$ -	$ 2,550,000
Spacecraft Bus Development and Testing	$ -	$ 250,000	$ 1,000,000	$ 3,000,000	$ 2,250,000	$ -	$ -	$ -	$ -	$ -	$ 6,500,000
Spacecraft bus (ESPA ring)	$ -	$ 250,000	$ 750,000	$ 500,000	$ 250,000	$ -	$ -	$ -	$ -	$ -	$ 1,750,000
Payload integration and testing	$ -	$ -	$ 250,000	$ 2,500,000	$ 2,000,000	$ -	$ -	$ -	$ -	$ -	$ 4,750,000
Launch Vehicle and Services	$ 100,000	$ 500,000	$ 71,000,000	$ 27,000,000	$ 10,000,000	$ -	$ -	$ -	$ -	$ -	$ 108,600,000
Launch vehicle	$ -	$ -	$ 70,000,000	$ 25,000,000	$ 5,000,000	$ -	$ -	$ -	$ -	$ -	$ 100,000,000
Launch integration support	$ 100,000	$ 500,000	$ 1,000,000	$ 2,000,000	$ 5,000,000	$ -	$ -	$ -	$ -	$ -	$ 8,600,000
Mission Operations	$ -	$ -	$ -	$ 250,000	$ 1,000,000	$ 4,000,000	$ 4,500,000	$ 4,500,000	$ 3,500,000	$ 2,500,000	$ 20,250,000
Mission operations and ground tracking	$ -	$ -	$ -	$ -	$ 500,000	$ 2,500,000	$ 2,500,000	$ 2,500,000	$ 2,000,000	$ 2,000,000	$ 12,000,000
Payload operations	$ -	$ -	$ -	$ 250,000	$ 500,000	$ 1,000,000	$ 800,000	$ 800,000	$ 800,000	$ 500,000	$ 4,650,000
Data analysis	$ -	$ -	$ -	$ 250,000	$ 500,000	$ 1,500,000	$ 2,000,000	$ 2,000,000	$ 1,500,000	$ 500,000	$ 8,250,000
Total	**$ 3,320,000**	**$ 9,300,000**	**$ 102,000,000**	**$ 42,500,000**	**$ 21,250,000**	**$ 5,850,000**	**$ 6,100,000**	**$ 5,700,000**	**$ 4,150,000**	**$ 2,700,000**	**$ 202,870,000**

Note: Launch vehicle costs could be drastically reduced if GDI is configured as a secondary payload using an ESPA ring.

Summary

The Geospace Dynamics Imager is an innovative observational concept to provide the first direct, global images of the solar wind-magnetosphere system. Global observations of the Earth's magnetosphere and its interface with the solar wind would provide the final link in achieving truly seamless Sun-to-Earth imaging when combined with other heliospheric measurements. The concept is based on the broad band detection of Thomson scattered sunlight by electrons both in the solar wind just upstream of the Earth's magnetosphere and in the Earth's magnetosphere, plasmasphere, and topside ionosphere. This new concept will provide unprecedented measurements with significant impacts on our basic scientific understanding of this coupled system, space situational awareness, and future modeling capabilities. Preliminary studies have shown that the proposed measurement is feasible with currently available technology. The instruments and mission concept we propose are based on the our extensive experience in measuring Thomson scattered light in the heliosphere with coronagraphs and white-light imagers on previous, current, and upcoming missions including SOHO LASCO, STEREO SECCHI, and WISPR on Solar Probe Plus. The Geospace Dynamics Imager measurement objectives of observing the solar wind incident upon the magnetosphere and the global response of the magnetosphere to solar wind drivers can be achieved with a small to medium-class mission.

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Commercial Access to Space for Scientific Discovery and Operations

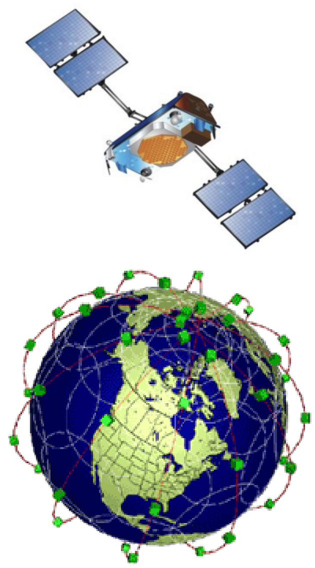
Leveraging broad new opportunities for cost-effective access to space for science

Lars Dyrud, H. Todd Smith, Larry Paxton, Chad Fish, Charles Sweson, Pontus Brandt, Gary Bust

Fewer than 500 scientific satellites and 500 people have been launched into space by government agencies. Commercial Space (non-DOD/NASA) have led the way in lowering costs and these developments promise to enable greater numbers of opportunities each year. The commercial use of space is anticipated to accelerate and will dramatically open new opportunities to address the frontiers of science. Addressing some of the most vexing basic science questions in magnetosphere, ionospheric and atmosphereic science, concerns non-local non-linear coupled system dynamics. The observations required to achieve the greatest scientific advances will require arrays of scientific sensors disttributed throughout the system gathering data simultaneously. This capability requires a change in the traditional approach in the implementation of scientific missions that are based on single or a few spacecraft and each typically cost $200M - $1B. While not all scientifically important orbits are available, sub-orbital, LEO, MEO and GEO provide excellent platforms for a range of in-situ and remote sensing sensors. Judicious and aggressive use of these opportunities for terrestrial magnetospheric, ionospheric, and upper atmospheric science could free up valuable resources for targetted missions addressing critical regions (as for instance MMS) and also for exploration missions to the Sun, L1, planetary magnetospheres and beyond.

Two broad types of commercial access to space are emerging manned/unmanned sub-orbital programs (Blue Origin, LLC; Dreamspace Group, Masten Space Systems, Inc.; Virgin Galactic LLC; XCOR Aerospace, Inc.), and hosted payloads on board commercial satellites (Iridium, Intelsat etc…). Each type of commercial space use has distinct scientific and cost saving potential. That these opportunities are real is demosntrated by the fact that the commercial sector is actively seeking commercial and federally supported hosted payloads and have accommodated this possibility in their space vehicle designs.

However there are several impediments that currently prevent scientists from taking advantage of these revolutionary opportunities. Pilot programs would be ideal avenues to advance and demonstrate the utility and benefit of removing these impediments and realizing the major cost, logistical, and time savings provided by commercial space flight opportunity. NASA’s Commercial Reusable Suborbital Research Program (CRuSR) is a great example of such a program designed to help support and guide companies in meeting anticipated research needs however; this program is only currently modestly allocated and not yet funded.



Iridium NEXT constellation of 66+ LEO satellites

Examples of Commercial suborbital spacecraft (XCOR's Lynx Mark I and Virgin Galactic's SpaceShipTwo)

Benefits to scientific utilization of commercial access to space:

1. Dramatically lowered costs $200,000 instead of $2-3M (suborbital research), $200M for constellation program instead of $2-5B (Iridium)
2. Significantly more frequent access
3. Compressed timeline from scientific idea to space measurement
4. Reduced barriers to entry for scientists less familiar with space measurements
5. Address previously impossible scientific topics, i.e. constellations that make global measurements
6. Continue to address critical operational societal and scientific needs while lowering costs to the taxpayer.

Current impediments to realizing these benefits:

1. The mismatched schedules of commercial space and government funding agencies must be resolved. Commercial satellites are typically built and launced in 24-36 months. Funding agency programs are not set up to respond to these opportunities on such a short time scale.
2. Unresolved risk and liability issues between industry and Government.
   Few or no sponsor mechanisms for providing support to projects utilizing the unique opportunities of commercial space.

To overcome these current obstacles and realize the significant benefits of utilization of commercial access to space we are making the following **recommendations**:

1. Firm government funding and support provided to the NASA CruSR program as well as adding additional funding opportunities for suborbital research, instrument development and education.
2. Initiate pilot programs to specifically fund hosted-payloads on commercial satellites to provide pathfinders for overcoming the above existing challenges.

We continue with a description of some existing efforts in both the hosted payload and sub-orbital areas that act to demonstrate some of the novel ideas within atmospheric and heliophysics that are being, and could be realized with future programs.

Program Name: AMPERE

Program PI: Brian Anderson, JHU APL

Program Management: JHU APL

Funding Agency: NSF

The Active Magnetosphere Polar Electrodynamics Response Experiment (AMPERE) is a facility that provides global measurement of the field-aligned Birkeland electric currents that link the Earth's magnetosphere and ionosphere. The AMPERE facility utilizes the Iridium Communications Inc. constellation consisting of more than 70 satellites at 780 km altitude circular near-polar orbits evenly distributed among six equally spaced orbit planes. As part of the avionics, each satellite carries a vector magnetometer which is sensitive enough to detect these Birkeland currents. The AMPERE program acts to demonstrate that previously impossible science goals are attainable at modest cost with these proposed private public partner projects

The state and dynamics of the magnetosphere-ionosphere (M-I) system are intimately linked to the Birkeland electric currents that flow between the magnetosphere and ionosphere along magnetic lines of force and which mediate momentum and energy transport between high and low altitudes. The currents are the coupling nexus of the system and reflect the entire solar wind M-I interaction. By making continuous observations of the Birkeland currents with truly global and nearly uniform coverage (see Figure 1) in both hemispheres independent of geomagnetic activity, AMPERE provides unprecedented capability to characterize the configuration and dynamics of the global field-aligned currents enabling major science advances across a broad range of M-I physics.

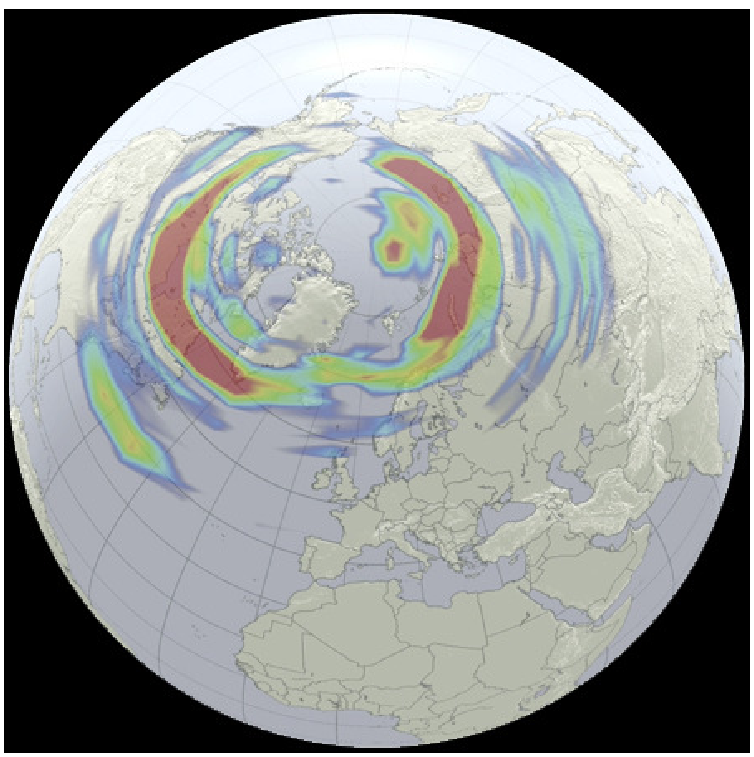


Figure 1 For 36 hours on Feb 14–15, 2010, AMPERE measured electric currents during a small magnetic storm. This view is from above the North Pole and slightly behind the Earth, with the Sun toward the top of the screen. Gray and blue colors represent weak currents, while greens, yellows and reds show

progressively stronger currents. This image shows the strong currents at the peak of the storm, intensifying as they move from the pole toward North America and Asia. The currents flow at heights of about 60–70 miles, but they can affect power grids, and major storms have caused widespread blackouts. Using AMPERE, scientists will soon be able to produce views like this nearly in real time – finally allowing us to see space weather as it happens.

Program Name: GEOScan: a Geosciences Facility from Space

Program PI: Lars Dyrud, JHU APL

Mission Management: JHU APL

Possible Funding Agency: NSF

Iridium Communications Inc. is launching a new generation of polar orbiting communication satellites in 2015-2017. Iridium has decided to place a hosted payload bay on each of the 66+ globally distributed satellites, which brings forth the possibility to host scientific sensors. Four primary factors make this an unprecedented opportunity for geoscience discovery, while holding the potential to affect a paradigm shift in the way we conduct science from space:

1) Truly global coverage provided by the constellation
2) Massively dense-space-based measurements enable revolutionary new techniques such as tomographic imaging.
3) Because Iridium Inc. is a telecommunications company, the logistical and cost barrier of transmitting massive amounts of data from 66+ satellites is REMOVED
4) Because we plan to build nearly 70 GEOScan pods we can take advantage of the cost savings of scale for science from space instead of the highly costly “one of a kind” methods of the past.

In order to take advantage of this new opportunity, we have devised a potential program named GEOScan, which consists of two complimentary main components, a community Hosted Sensor component where individual PI’s provide and deliver unique sensors on one or more GEOSCAN pods, and 2) System Sensor science payloads, where two common sensors are placed on ALL GEOScan pods to conduct high impact and broad value system science and imaging investigations (examples include GPS radio occultation and atmosphere/ocean or limb imaging). Each 2-3U GEOScan pod that will be placed in all 66+ Iridium NEXT hosted payload bays and conform to the now defined Iridium SensorPod specification.

The GEOScan program will enable breakthrough science by uniformly sampling the Earth air and space environment in higher resolution with truly global coverage. The density of the measurements will enable new techniques such as tomographic imaging that allow viewing the Geo-environment in far greater detail than previously possible. These data will allow research into the untouched topics including global change that require both simultaneous and global sampling, and will provide an unparalleled source of data for both weather and space weather assimilative models. The success of the NSF funded AMPERE project that includes APL and Iridium acts as a model for GEOScan and provides inspiration for the possible science shifts in understanding that arise from global space based measurements.

Program Name: Storm Time Energy And Dynamics Explorer (STEADE)

Program PI: Dr. Charles Swenson, Utah State University

Mission Management: Space Dynamics Laboratory – Utah State University

Proposed Funding Agency: NASA

Program Description: Energy is deposited into high latitudes of Earth's upper atmosphere by a number of transporting sources, including gravity waves from below and solar originating electromagnetic, momentum (i.e., kinetic particle precipitation), and irradiation energy fluxes from above. The electromagnetic energy flux, due to continually changing solar-magnetospheric interactions, varies both temporally and spatially across the Earth's polar regions. It is a significant, and quite often the dominant, converging source in the ionosphere and thermosphere [e.g. [1]] as much of the polar region is dark throughout the year.

STEADE will globally measure electromagnetic energy flux into and the resultant heating of Earth's upper atmosphere at unprecedented temporal and spatial scales, thus providing a system response observation of sun-earth interaction. Specifically, STEADE will address the NASA Heliophysics Roadmap research focus area H2, "Understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects", and the subsequent priority investigation of "How do the magnetosphere and the ionosphere/thermosphere systems interact with each other?"

Commercial Suborbital Opportunities

Numerous companies are in the process of developing suborbital spacecraft many of which are planned to start operational launches in 2011. Initially, companies developed a business plan that targets the space tourism industry with a cost of $200,000 or less per seat. However, it has become apparent that the scientific community may provide a more stable and long term customer for these opportunities. Currently, most of these spacecraft are planned to attain approximately 100km above the Earth's surface for a period of time on the order of minutes in microgravity. The scientific community currently pays in excess of $1.5M to conduct this type of research using traditional rockets. Therefore, commercial suborbital spacecraft offer the possibility of conducting the same research for a small fraction of the current cost, with the added benefit of potentially flying a scientist along with the experiment to ensure proper operation and safe return of the instruments.

Such low cost access to space offers new opportunities in our field in relation to scientific research, instrument development and STEM education. In-situ observations of the Earth's atmosphere are limited because this altitude is too high for balloons and too low for orbital spacecraft. Such observations (neutral particle composition and density, for example) conducted on a low cost and frequent basis will greatly increase our knowledge of the Earth's atmosphere. Additionally, such opportunities provide a low cost method of testing and validating new instrument concepts (beyond ground based laboratory testing) prior to flying them on heliospheric missions. This capability should more rapidly advance the technical state of the art. Finally, low cost commercial suborbital capabilities offers a much greater opportunity to directly involve university students in designing, developing and operating space-based scientific investigations and experiments. Such opportunities could dramatic improve future scientist education and retention.

These potential benefits from commercial suborbital spacecraft are rapidly advancing. Direct scientist interaction with immerging companies has already improved potential capabilities in regards to external payload bays for direct access to space and possible boosting of small payloads into orbit. Additionally, some of the companies are starting to design future spacecraft that will attain higher altitudes and thus expand the possibility for ionospheric (and above) research. This immerging technology is being developed and it is critical that the US continues to encourage this development through NASA supported and funded programs. Commercial spaceflight is advancing rapidly and if NASA does not support and lead this activity, there is a risk that NASA (and the US) could be left behind as the technology advances and becomes economically viable. This does not represent a loss of for NASA initiatives but more of an expansion to facilitate the safe and expedient exploitation of commercial access to space.

MORE/ORBITALS: An international mission to advance radiation belt science

Scot Elkington and Xinlin Li
LASP, University of Colorado at Boulder

Executive Summary

This whitepaper proposes support for the MORE/ORBITALS mission, an international collaboration to build a spacecraft to study the dynamical evolution of the radiation belts. Key features of this mission include a fully-instrumented platform capable of making critical radiation belt measurements, in an orbit specially designed to take advantage of existing geosynchronous and ground-based observations. The MORE/ORBITALS collaboration will significantly extend and augment the science return from the planned NASA RBSP mission.

ORBITALS is a mission proposal to the Canadian Space Agency to design a radiation belt mission that takes particular advantage of the existing Canadian array of magnetometers and riometer network, and is currently in a Phase A concept study. MORE (Mission of Opportunity, Radbelt Explorer) was proposed to the 2006 NASA RBSP Mission of Opportunity Program to provide an instrument package of particle and field detectors for the ORBITALS mission, and was selected for Phase A study. Many of the instruments planned for the MORE package are identical or highly-similar to instruments selected for the RBSP mission, giving the MORE instruments a high degree of technical readiness and a well-constrained cost envelope. The MORE/ORBITALS project will provide a blueprint for leveraging international collaborations in a fashion that maximizes net scientific return while minimizing expenditure of US resources.

Relevance of the Mission: Outstanding Questions in Radiation Belt Research

Recent advances in understanding the physics and dynamics of the radiation belts has benefitted from sustained observations of particles and magnetic fields at geosychronous, with the Polar, Cluster, and Themis missions providing valuable insight into processes occuring over a broader range of radial distances and latitudes. These observations have been augmented by advances in theoretical understanding of the physics driving the dynamical variations in the radiation belts, and improvements in physical and empirical models of the geospace environment. In spite of these efforts, questions remain regarding the processes underlying the formation and loss of the radiation belts. We outline some aspects of these fundamental questions below.

Which physical processes produce radiation belt enhancement events? Processes leading to radiation belt enhancement events can be broadly categorized as being a result of either radial transport of electrons into regions of stronger magnetic field strength, leading to energization through conservation of a particle's magnetic moment; or as a result of local interactions with plasma waves which are capable of resonantly accelerating particles through interaction with the particle's gyromotion. Radial transport may occur on timescales ranging from a few seconds to several days. During the storm sudden commencement associated with the superstorm starting on March 24, 1991, an interplanetary shock formed by a coronal mass ejection led to the impulsive injection of electrons from beyond geosynchronous orbit [*Li et al.*, 1993] into the slot region at $\sim 2.5 R_E$ within a minute, resulting in a new electron radiation belt with a strongly peaked energy spectrum at ~15MeV. More often the response of radiation belt electrons to solar wind variation occurs over periods of hours to days. Low frequency, long wavelength perturbations of the magnetopause boundary can transfer energy to ULF wave modes in the inner magnetosphere [*Claudepierre et al.*, 2008], leading to the stochastic transport of particles through radial diffusion on appropriate timescales depending on magnetospheric activity. Large-scale convective electric fields transport plasmas radially inward to the radiation belt trapping region for subsequent acceleration, and may act to enhance the radial diffusion of particles in the inner magnetosphere [*Schulz and Lanzerotti*, 1974]. Local acceleration may occur as a result of particle interactions with waves with periods commensurate with the gyromotion (kHz) of the particle.

For example, pitch angle and momentum scattering may occur effectively through electron interactions with whistler-mode chorus waves outside the plasmapause [e.g. *Horne and Thorne*, 1998]. Test particle and local diffusion simulations suggest that such waves can energize electrons by $>$1 MeV in several hours, although this mechanism depends strongly on the amplitude, phase velocity, and direction of propagation of the whistlers.

Outstanding questions related to the enhancement of radiation belt electrons include *What processes are responsible for radial transport and acceleration?* Understanding the occurence, spectrum, and mode structure of magnetospheric ULF wave modes is key for predicting the diffusive effects of these waves on the radiation belts; understanding variations in the large scale convection field will provide insight into the transport and acceleration of seed populations of electrons for subsequent acceleration. *What is the effect of localized acceleration processes on the radiation belts?* Occurence, morphology, and spectral characteristics of whistler waves and other electromagnetic variations at kHz frequencies are necessary for predicting the effects of these waves on electrons comprising the belts. *How do we distinguish among competing or concurrent acceleration and transport mechanisms?* In theory the distinguishing effects of radial transport and local acceleration processes will be manifest in the evolving radial phase space density profile of the radiation belts. Equatorial particle measurements at a relatively high cadence and at a range of radial distances are required to unambiguously determine the time evolution of the radial profile. *How do we predict and model the spatial, spectral and temporal characteristics of radiation belt enhancements?* It is known that radiation belt responses are closely correlated with solar wind velocity, with an appropriate 1-2 day time lag [*Paulikas and Blake*, 1979]. Comprehensive particle and field measurements are required to make the physical connection between solar wind and magnetospheric activity that will allow models to predict the radiation belt response in advance.

What are the dominant mechanisms for relativistic electron loss from the radiation belts?

There are a number of possible mechanisms by which electrons may be lost from the magnetosphere. Among them are (i) adiabatic response of trapped particles under changing geomagnetic field conditions. This is an apparent loss only which results from the outward motion of particles during the magnetic flux decrease associated with ring current enhancements [*Kim and Chan*, 1997; *Green and Kivelson*, 2004]; (ii) Loss of particles to the magnetopause. During times of high magnetospheric compression the magnetopause may intersect previously-closed drift orbits; and (iii) Scattering of particles into the bounce loss cone via interaction with various magnetospheric waves. Violation of the first or second invariant can change the bounce motion of particles and cause them to be lost to the atmosphere.

Outstanding questions regarding the loss of particles from the radiation belts addressed by this mission include *What processes are responsible for relativistic electron loss?* Multipoint examination of plasma waves and background field configuration is necessary to distinguish among the possible loss mechanisms outlined above. *Which wave/particle scattering processes are most effective during different geomagnetic activity levels?* The relation between the temporal variability of relativistic electron precipitation patterns and the occurence of different wave modes in the inner magnetosphere has not yet been established. *What are the contributions of magnetopause shadowing to relativistic electron loss?* The relative effect of losses due to global geomagnetic field morphology will require both particle and field measurements at a range of L values. *What are the average loss rates during storms?* Understanding the aggregate effect of the range of possible loss mechanisms is key in understanding and modeling the global results of geomagnetic activity.

Does the ring current play a direct role in radiation belt electron enhancements and losses?

Many of the most important energization processes in the Earth's magnetosphere operate with the greatest intensity for the 5-20 hour periods of the main phase of geomagnetic storms. This occurs deep in the inner magnetosphere where they are largely hidden from the view of the majority of scientific spacecraft. Many of the spacecraft previously designed to study magnetospheric dynamics have had apogees at 10-30 R_E and have orbital periods ranging from 20 hours to several days. Such spacecraft spend only a very small fraction of their time within r$\sim$6 R_E. The inner magnetosphere is relatively under-sampled by in situ spacecraft and as a result E- and B-field dynamics are poorly understood there, particularly during storms. ORBITALS data will provide essential coverage of the inner magnetosphere that would enhance this understanding, as well as being important for discerning inner magnetospheric ring current dynamics and critical for the computation of accurate radiation belt particle distribution functions.

Fundamental questions that will be addressed by this mission include *What role does the ring current play in the storm-time wave phenomena that affect radiation belt electrons?* Understanding the evolution of the plasma anisotropies that lead to wave growth will provide insight into the effects of these waves on both radiation belt acceleration and loss. *How important are the ring current effects on the electric and magnetic fields that cause transport and diffusion of radiation belt electrons?* The ring current is responsible for producing high-mode number poloidal ULF waves that result in the transport and diffusion of relativistic electrons [*Elkington et al.*, 2003; *Ukhorskiy et al.*, 2005]. The ring current may also shield the inner magnetosphere from the large-scale convective electric fields [*Rowland and Wygant*, 1998] that transport electrons earthward and provide and additional source of radial diffusion [*Schulz and Lanzerotti*, 1974].

Space weather effects. Understanding the physical processes outlined above is a primary goal of the Sun-Solar System Connection Division of NASA. These questions are critical to achieving two major NASA science objectives: (1) Understand our changing Sun and its effects throughout the solar system (i.e., "Understand the space environment of Earth and other planets" and "Understand the effects of solar variability on the heliosphere"); and (2) Chart our destiny in the solar system (i.e., "Develop the capability to predict space weather"). Predicting the state of the near-Earth radiation environment is a high priority national objective [*National Space Weather Program Working Group*, 1997; *SEC Roadmap Team*, 2003].

ORBITALS will provide continuous measurements of electrons and ions from the inner belt to close to geosynchronous orbit at energies (from ~keV to the 10-100 MeV range) that are important for space weather and satellite charging [*Baker*, 2002]. These measurements will be used as inputs for the development of the next generation of radiation belt specification models to replace AP-8 and AE-8. Onboard deep-dielectric charging monitors, as well as total dose and single event upset (SEU) monitors, will also measure the on-orbit effects of the space environment encountered by ORBITALS. The new fundamental understanding that will result from addressing these objectives will lead directly to improved space weather specification models and hence to the mitigation of space weather effects in the design of operational satellites.

Mission Concept and Technical Description

The ORBITALS mission is being developed by the Science Team in collaboration with the identified industrial partner Bristol Aerospace Limited of Winnipeg. The ORBITALS bus design is based on the MAC-200 bus being developed as a Universal Small Satellite Bus – a three-axis stabilized design with redundant, cross-strapped avionics. The SmallSAT bus will be modified to meet the mission radiation and magnetics requirements. In addition to adding radiation shielding, hydrazine thrusters will replace the standard reaction wheels and torque rods to aquire attitude and provide and maintain spin. The baseline spacecraft structure is hexagonal shaped with the solar panel at one end of the structure. The body mounted solar panel is designed and laid out to reduce magnetic fields to levels acceptable to the ORBITALS/MORE mission.

The ORBITALS science team is led by Dr. Ian R. Mann from the University of Alberta, and currently principally comprises solar-terrestrial scientists and proposed instrument providers from leading Canadian and US institutes. The mission follows a philosophy of utilizing well-developed instrument technologies to maximize the likelihood of mission success; the scientific innovation comes from the targeting of an orbit in the relatively under-explored equatorial inner magnetosphere.

The equatorial ORBITALS orbit, a 2.0 $\times$ 6.3 R_E geotransfer orbit with a low inclination ($<15°$), is designed to span the slot region and extend across the outer belt to close to geosynchronous orbit. Through careful orbit selection, the satellite will also enjoy very long-lasting magnetic conjunctions to the extensive groundbased instrumentation in the Canadian Geospace Monitoring (CGSM) program as well as to other US operated ground-based instrumentation in this sector. The orbit generates regular long-lasting apogee conjunctions close to the GOES East and West satellites. The ORBITALS bus will have a nominal spin period of around 10s, with the spin axis pointing toward the sun. This allows single look direction particle instruments to measure 2D pitch angle distributions in a plane containing the nominal background magnetic field once per spin. For particle instruments with 2D coverage, full 3D particle distribution functions will be produced once per spin. In the baseline payload, particle instruments monitoring ions and electrons across a wide range of energies from eV to 10s of MeV will be complemented by boom mounted fluxgate and induction coil magnetometers, as well as an electric field and waves (EFW) instrument containing crossed ~90m tip-to-tip wire booms in the spin plane based on the CRRES and Polar designs (Wygant et al., 1992a; Harvey et al., 1995). In the following, we discribe the individual instrument on MORE suite.

The **EEPS** instrument consists of two Magnetic Electron Spectrometers (MagES-Low; MagES-Med) and a E-32 Medium Ion SpecTrometer (MIST) which is integrated within the MagES-Med sensor. Each magnetic spectrometer is in a separate mechanical and electrical package. Each of the EEPS magnetic chambers has a disk-loaded external collimator to constrain the arrival direction of the electrons and reduce stray response from electron scattering. Anti-scattering elements are also used internal to the two MagES units. The incoming electrons are momentum analyzed and deflected 180° onto a sixteen pixel solid state detector strip from Micron Semiconductors in each unit. The MagES-Low measures electrons from 30 to 300 keV and MagES-Med measures electrons from ~0.3 to 1.9 MeV. 20-1000 keV ions are spread out across a six pixel strip detector at the rear of the MagES-Med unit, according to their magnetic rigidity allowing the possibility to separate O from H at >50 keV/ion. Engineering Models for MagES-Low, -Med, and -High have been built and tested, the flight models will be delivered in 2011.

REPT measures electrons of energies ~2 to ~20 MeV with special emphasis on the ~2 to 10 MeV science requirements range. These energies are inclusive of both "typical" as well "extreme" energization events such as the one observed by CRRES during March 1991. In addition, the REPT also measures protons ranging from ~20 to ~100 MeV. Proton measurements not only enable studies of inner zone proton processes such as SEP trapping but also facilitate a clean differentiation between measured electron and proton events, especially in the inner belt. This separation is crucial in the study of formation of new electron belts deep inside the magnetosphere, such as the event observed during October-November 2003 (Baker et. al, 2004). The science requirements driving the nearequatorial orbit of ORBITALS and MORE define the REPT design. REPT is required to measure high electron fluxes at >1 MeV without saturation and pileup while measuring lower flux, higher energy populations with sufficient statistics. The instrument design is based upon the dE/dx-E technique and measures electrons and protons with an energy bin resolution, i.e., delta $\Delta E/E$ of 30%. Particle flux measurements are collected on a 36 spin sector basis. With the 30° instrument Field-of-View (FOV) pitch angle is provided at ~10° using ground based deconvolution. The REPT sensor comprises a stack of silicon solid-state detectors in a telescope configuration enclosed in an aluminum-tungsten shield. A front-end diskloaded collimator sets the FOV, which is a circular cone of 30°. A beryllium disc 2 mm thick, located at the back end of the collimator stops electrons below ~1 MeV. The solid state detector stack is made up of 9 separate detectors whose total thickness is 24 mm. The stack is surrounded by a tungsten layer 7 mm thick, which is further encased by an outer aluminum layer 10 mm thick. This shielding is equivalent to the continuous slowing down approximation range for ~30 MeV electrons and ~100 MeV protons. The collimator acceptance angle of 30° and the front detector sizes result in a nominal geometric factor of ~0.2 cm2-sr, for electrons in the 2 - 5 MeV range. This results in count rates that are manageable by the electronics at high fluxes, and yields statistically significant counts at low fluxes. Engineering models of REPT for RBSP have been built and tested, LASP engineers are on track to deliver the flight models in 2011.

The **EFW** instrument is based on the electric field instruments on the ISEE-1, CRRES, Polar, FAST, Cluster spacecraft, THEMIS, and most recently for the RBSP mission. The EFW consists of a main electronics box and four boom deployment units mounted at 90° intervals on the periphery of the spacecraft. The boom deployment units, boom cables, and sensor electronics will be provided by the University of California at Berkeley (UCB). Inside the main electronic box are a digital signal processing board, an instrument DPU, and burst memory. The primary analog and digital signal processing for the ORBITALS search coil magnetometer signal processing is included in the EFW instrument. In addition, the analog signal from the ORBITALS DC magnetometer is passed to the EFW DSP board for internal data processing. The electric field booms are deployed and centripetally held in the spin plane of the spacecraft. One pair has a tip-to-tip length of 80 m and the other 100 m. The different boom lengths are used to calibrate the electric field measurements and assess errors. The electric field instrument determines the two-dimensional electric field vector in the spin plane of the spacecraft (Y-Z GSE) by measuring the potential difference between spherical sensors at the ends of the two opposite boom pairs.

CODIF is a mass per charge ion composition sensor with medium angular resolution. Its mass-resolving spectrometry is highly sensitive with an instantaneous FOV of 8° in the spin plane and 360° out of the spin plane to measure 3D distribution functions of the major ion species, within one spin period of the satellite. Typically the species include H+, He++, He+ and O+. The sensor primarily covers the energy range between 0.02 and 38 keV/charge. The instrument combines the selection of incoming ions according to energy per charge by electrostatic deflection in an electrostatic analyzer with post-acceleration by up to 20 keV/e and subsequent time of flight (TOF) analysis. The electrostatic analyzer (ESA) is of a toroidal top-hat type with a uniform response over 360° of polar angle. The analyzer consists of an inner toroid, to which a variable negative potential is applied, an outer toroid with a cut-out at the top, and a top-cap lifted above the outer toroid. Both the outer toroid and the top-cap are normally held at ground potential, thereby exposing no high voltage to the outside world. A beam of parallel ion trajectories entering the aperture is focused at the exit plane of the analyzer. This location determines the incident polar angle of the ions. With a cross-plate voltage of 2–5200 V (varied with logarithmically spaced steps), the energy range is 20–38,000 eV/e. The analyzer has an intrinsic energy resolution of delta E/E $\sim$0.13. The full polar angle of the analyzer is divided into 16 pixels of 22.5° each. The full energy sweep will be performed 32 times per spin. Thus, a two-dimensional cut through the distribution in polar angle with 11.25° resolution in azimuthal angle is obtained every 1/32 of a spin period. While the intention is to fly the CODIF spare electronics as-is, designs are available to replace the key subsystems if any problems arise due to the age of the instrument.

Mission Operation and Science Operations. The MORE Science Operations Center (SOC) will monitor and control the MORE instruments and provide a single interface to the Canadian Mission Operations Center (MOC). The SOC will be responsible for preparing observing sequences and command loads and for monitoring and maintaining the health and safety of the MORE instruments. Instrument commands will originate in the SOC and be given to the MOC for transmission to the spacecraft. The SOC will be implemented by LASP, which is probably the most experienced university lab in the U.S. at operating spacecraft and their scientific instruments. Most of the facilities, personnel, hardware/software needed to implement the SOC are already in place.

The SOC will work with the instrument team leads to plan observations and will schedule scientific observations, generate stored command loads, and forward the loads to the MOC. Routine observing sequences will be generated by the SOC following rules and guidelines set forth by the instrument team leads. Special observations can be requested by the instrument team leads and the SOC will integrate them into the sequence. LASP will use its existing OASISPS planning and scheduling software to generate observing sequences.

The MORE data processing plan combines distributed processing at the instrument Co-I sites with rapid production of merged data products at the central SOC and Science Data Center (SDC). The SOC will generate the Level-1 and Quicklook data. The SDC data products will include, among others, the complete Level-2 data and analysis software tools. The MORE team is committed to making the data available rapidly to the entire scientific community, and to share educational data products and information to the public.

Estimate of Costs

Our cost estimate for the proposed mission is outlined in Table 1, and is based on the following:

(1) MORE had completed its phase A study ($1M) and gone through its Concept Study Report (CSR) review in 2007. The review panel agreed with the original cost estimate. Afterwards NASA provided additional $0.5M for further risk reduction. Therefore MORE is currently ready to step into Phase B directly.

(2) MORE consists of 4 instruments, three of them (REPT, EFW, and EEPS) are basically identical to their the other two copies that have been built for NASA/RBSP mission. Thus the cost for their design and building (Phase B/C/D) will be greatly reduced, such savings were not included for the original budget (2007). As for the 4th instrument, CODIF, its detector is still sitting in the clean room, already built and tested 10 years ago as the spare one for CLUSTER mission (the other four CODIF onboard CLUSTER are still taking measurements). Since 2007, UNH has developed new electronics for CODIF using their own internal support (this will be an additional saving with respect to 2007 Budget).

Table 1: MORE Estimated Expenses

Phase B (1 yr)	
Total	$7,116k
Phases C and D (2-3 yrs)	
REPT	$2,995k
EFW	$2,800k
CODIF	$2,776k
EEPS	$3,636k
Instr. Int. and Test	$692k
PM/Miss. Analysis/SE/Miss. Assu.	$3,666k
Science Team Support	$1,789k
Prelaunch GDS/MOS Development	$2,297k
Total	$20,651k
Phase E (2 yrs)	
Total	$5,616k
MO and DA	
Total	$2,242k
Science	
Total	$3,374k
Grand Total	**$33,483k**

(3) The cost for instrument integration and test, management, mission analysis, mission assurance, interface with the s/c bus and prelaunch test, MO/DA, and science, etc, will be kept the same as the 2007 budget (small inflation occurred since then, however, great heritage and managment experience were gained from RBSP mission).

Viability of the MORE/ORBITALS Mission

ORBITALS will make the measurements necessary to gain fundamental new understanding of the relative importance of different physical acceleration and loss processes that are hypothesized to shape the energetic particle populations. ORBITALS will provide the raw radiation measurements at Middle Earth Orbit (MEO) altitudes necessary for the development of the next-generation radiation belt specification models; on-board experiments will monitor the dose, single event upset, and deep-dielectric charging of electronic components on-orbit.

MORE/ORBITALS will complement and extend the RBSP mission, providing better temporal cadence, greater local time coverage, and better linkage between ground observations and geosynchronous measurements than the RBSP spacecraft alone could otherwise provide. The combination of MORE/ORBITALS with the RBSP program will be crucial for closure on many of the LWS Geospace Mission objectives:

- With its 13.6-month precession rate, MORE/ORBITALS complements the 21-month precession of the RBSP orbit through varying separations in local times, allowing a critical global view of both the particles and the fields that drive their dynamics;
- MORE instruments increase the temporal cadence at which radial phase space density observations can be made, this being essential to distinguish among the competing effects of transport, acceleration, and loss;
- The ORBITALS apogee extends beyond that of the RBSP mission, closer to geosynchronous orbit, and thereby provides a means of evaluating seed populations and boundary conditions pertinent to the transport and acceleration of plasmas observed by the near-Earth RBSP spacecraft;

- The low inclination of ORBITALS will allow effective comparison of particle and field variations with latitude, thus providing critical information for next-generation space weather models; and
- ORBITALS' daily and long-lasting magnetic conjunctions with US and Canadian groundbased instrumentation will enable us to form space weather maps in the context of the continuous, global information from ground observations.

The MORE/ORBITALS mission will contribute significantly to NASA Research Objective 3B.1, to *understand the fundamental physical processes of the space environment from the Sun to Earth*, and Objective 3B.3, to *develop the capability to predict the dynamic conditions in space in order to maximize the safety and productivity of human and robotic explorers* [*NASA Science Mission Directorate*, 2006]. Because many of the instruments planned for the MORE/ORBITALS mission have already been through Phase A development work and are substantially similar to those being built for the NASA RBSP mission, the MORE instrument package has gained a significant level of technical readiness and reduced developmental costs. Partnering with the Canadian Space Agency in this effort will allow significant scientific return without the substantial expenses associated with procuring a spacecraft bus and launch vehicle. A successful MORE/ORBITALS project will provide a blueprint for leveraging international collaborations in a fashion that maximizes net scientific return while minimizing expenditure of US resources.

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The Magnetospheric Constellation Mission

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It has been several years now since the original concepts for magnetospheric constellations were put forward and discussed. In the mean time the global physics-based, kinetic and MHD models of the magnetospheric system have become quite sophisticated and our limited in situ measurements are combined with the models in an attempt to grasp a mental picture of how the system works as a whole. In the intervening years we have been able to form better images of parts of the system using remote sensing using visible and UV cameras and neutral atom imaging. However these do best in the inner magnetosphere/ionosphere parts of the system. The large scale region of the near earth magnetotail with its complex plasma flows, currents and reconnection cannot be "imaged" in a global manner, yet. With the evolution of technology that has occurred and the current intense focus on smallsat and microsat missions such as the ongoing THEMIS and upcoming cubesat missions, it is time to revisit The Magnetospheric Constellation Mission (MagCon) concept. THEMIS has shown, with great success, what can be done with a small subset of the original Magnetospheric Constellation. The MagCon mission holds out a promise of providing a dense-net of measurements that, much the same way that was done in meteorology, can be combined with models and/or simulations to extract both a microscale and macroscale view of the magnetosphere. At the same time, the net of measurements will constrain the models and provide the information necessary to improve them.

The MagCon concept was studied in some detail by a NASA Science and Technology Definition Team and the results of the study were published as a NASA report entitled "The Magnetospheric Constellation Mission Dynamic Response And Coupling Observatory (DRACO): Understanding the Global Dynamics of the Structured Magnetotail" (NASA/TM—2001–209985). The contents of the report are summarized in the executive summary which is presented below for reference.

The proposal here is to consider, once again, the original Magnetospheric Constellation Mission concept for implementation in the next decade. It will require a reexamination of the state of technology readiness, given the advances that have occurred since the original study. The capabilities and limitations of current and projected launch vehicles will have to be reviewed in light of the requirements imposed by such a mission.

The Magnetospheric Constellation Mission Dynamic Response And Coupling Observatory (DRACO): Understanding the Global Dynamics of the Structured Magnetotail

Executive Summary

Magnetospheric Constellation Dynamic Response and Coupling Observatory (DRACO) is the Solar Terrestrial Probe (STP) designed to understand the nonlinear dynamics, responses, and connections within the Earth's structured magnetotail, using a constellation of ~ 50-100 distributed vector measurement spacecraft. DRACO will reveal magnetotail processes operating within a domain extending 20 Earth radii (R_E) across the tail and 40 R_E down the tail, on spatial and time scales accessible to global circulation models, i.e., ~ 2 R_E and 10 seconds. Visualizing and understanding them will require observations analogous to a network of weather stations distributed within this domain. DRACO will reveal simultaneously for the first time both the global spatial structures and the time variations of the magnetotail. It will determine which phenomena are responses to solar wind inputs and which occur as a result of internal instabilities. In particular, it will reveal the locations and extents of the instabilities that trigger the explosive release of solar wind energy, mass, and momentum stored within the magnetotail, how these entities are transported, and the means by which magnetotail phenomena are propagated between regions and to the auroral ionosphere.

The magnetotail is a critical volume of the geospace environment wherein global circulation of magnetic fields and plasmas is regulated in response to changing solar wind conditions. In it, impulsive localized flow bursts launch and dissipate, powerful electrical currents form and evolve abruptly, and magnetic energy is explosively converted to particle energy. The fundamental plasma process known as magnetic reconnection is thought to occur during substorms, an important building block of "space weather." These are recurrent energy releases that become more frequent during magnetospheric storms. The dynamism and turbulent evolution of the magnetotail have humbled our efforts to observe and understand it using individual spacecraft. The magnetotail magnetic fields and plasmas do possess an underlying, slowly varying coherent structure, but strongly turbulent flows and fields are usually large compared to the mean field or flow. Thus, globally coherent pictures of the system dynamics become lost in the "noise" of individual measurements. Despite over 30 years of research with ever more sophisticated instrumentation on ever larger and more complex spacecraft, fundamental questions concerning the dynamic response of the magnetotail remain unanswerable. Accordingly, scientific progress has slowed. Intelligent, reasonable scientists cannot reach consensus on these issues, not for lack of models and theories, but because of a lack of relevant measurements. Neither current single spacecraft nor tight groups of spacecraft can resolve these fundamental controversies.

To provide the first ever global time-evolving vector field and streamline images of this important region, DRACO will use rapidly developing technologies to deploy a "constellation" of nanospacecraft. With resources of ~ 10-20 kg and 10 W apiece, 50-100 nanosatellites will be deployed in highly elliptical, equatorial orbits with common perigees of 3 R_E, and apogees distributed from 7 to 40 R_E, yielding mean inter-spacecraft separation of ~ 1-2 R_E.

The nominal DRACO mission has a design lifetime of 2 years, and is currently scheduled for a 2010 launch. While the enabling technologies for DRACO are developed or in development for the ST-5 Nanosat Constellation Trailblazer mission of the New Millennium Program, additional resources are required to demonstrate mass manufacturability and to optimize miniaturization while preserving functionality. With such resources, DRACO development could be accelerated with the launch as early as 2008.

Magnetospheric Constellation DRACO represents the logical outgrowth of a sequence of STP missions, designed to explore plasma transport and energy conversion processes over spatial sizes ranging from the distance to the Sun to the size of low-energy particle gyro-orbits. The Magnetospheric Multiscale (MMS) mission will focus on the smallest scale, microphysical processes occurring within and near magnetospheric boundary layers: magnetic reconnection, charged particle acceleration, and eddy turbulence. It will serve as the plasma physical "microscope," investigating scales too small to be resolved by global circulation models. In contrast, DRACO is designed to be a "meso/macro-scope" for the magnetotail. It will resolve persistent controversies by providing the required observations. Ultimately, it will yield a new understanding on which we shall build a predictive science of next-generation magnetospheric meteorology, adding to our collective body of knowledge relating to complex nonlinear dynamical systems.

Magnetospheric Constellation DRACO Highlights:

- DRACO will answer the following questions: How does the magnetotail control energy flow? What processes control magnetotail structure and dynamics? How do the physical processes and regions couple over the hierarchy of scales?
- Leads to closure of crucial magnetotail controversies that have remained unresolved for more than 30 years, owing to lack of coordinated multipoint observations.
- Single Delta launch creates a magnetotail constellation with possible launch in mid-2010 or earlier.
- 50-100 spacecraft with 10 sec time resolution, at mean separation of ~ 1-2 R_E over ~ 20 x ~ 30 R_E domain, resolve all features of global circulation models.
- Primary science accomplished annually when the constellation sweeps through the magnetotail. Ancillary magnetospheric/magnetosheath/solar wind science accomplished during balance of each year.
- New technology requirement is for miniaturization and mass manufacturability of nanosatellites and their instrument payloads.

Mission to Understand Electron Pitch Angle Diffusion and Characterize Precipitation Bands and Spikes

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Pitch angle diffusion into the atmospheric loss cone is a major cause of electron losses within the inner magnetosphere. When measuring the electron pitch angle distributions at the magnetic equator, it is difficult to assess whether pitch angle transport is uniform throughout the distribution or whether it is stronger over one part of the distribution relative to another. At moderately high L values, for example in the regions mapping near and above geosynchronous orbit, "bands" (see Fig. 1) of electron precipitation are commonly observed by low altitude polar orbiting spacecraft [Blake et al., 1996; Fritz, 1968; Vampola, 1971; Vampola, 1977]. Sometimes the magnetic field at these L values can become strongly stretched, especially during magnetically active and intense ring current periods, and the field's radius of curvature becomes small enough to cause loss of electron adiabaticity. This has also been observed, [Imhof et al., 1977, 1978, 1979, 1991]. Another kind of precipitation has been observed, called micro bursts [Blake et al., 1996, Lorentzen, et al., 2001a, 2001b; O'Brien et al., 2003] that can extend over wide range of L values in the outer radiation zone. It is clear that not all the precipitation bands and bursts are generated by the same process. But, it is thought that the majority of the precipitation bands and microbursts observed at low altitudes are caused by wave-particle interactions.

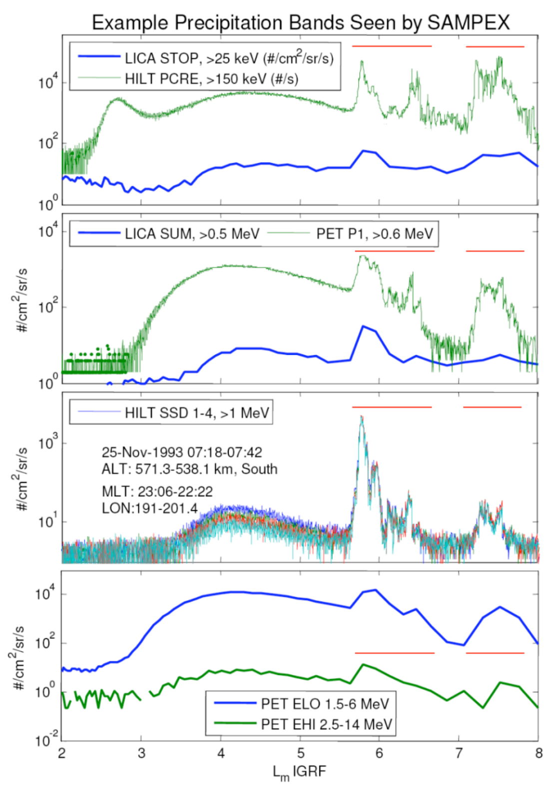

Figure 1. Example of multiple precipitation bands observed by SAMPEX during quiet conditions. The various panels indicate that the bands were observed from 25 keV to several MeV.

Historical low altitude observations indicate that while the electrons in the precipitation bands are isotropic at low altitudes, the corresponding electron fluxes at the magnetic equator are relatively unchanged (see below and Vampola, 1977). Koons et al [1972] reported a single case of pitch-angle isotropy over both loss cones at 4500 km, L ~ 5.6, suggesting that the observing satellite was in the actual scattering region. Coincident with the scattering were strong electrostatic waves from 400 Hz to 7.4 kHz, possibly proton cyclotron frequency waves Doppler shifted by the satellite motion. Koons et al. [1972] estimated that the electrostatic wave power was sufficient to drive the electrons to strong pitch angle diffusion. This implied that the precipitation bands were low altitude phenomena wherein the strong waves essentially enlarged the loss cone for the electrons while leaving the equatorial distribution unaltered.

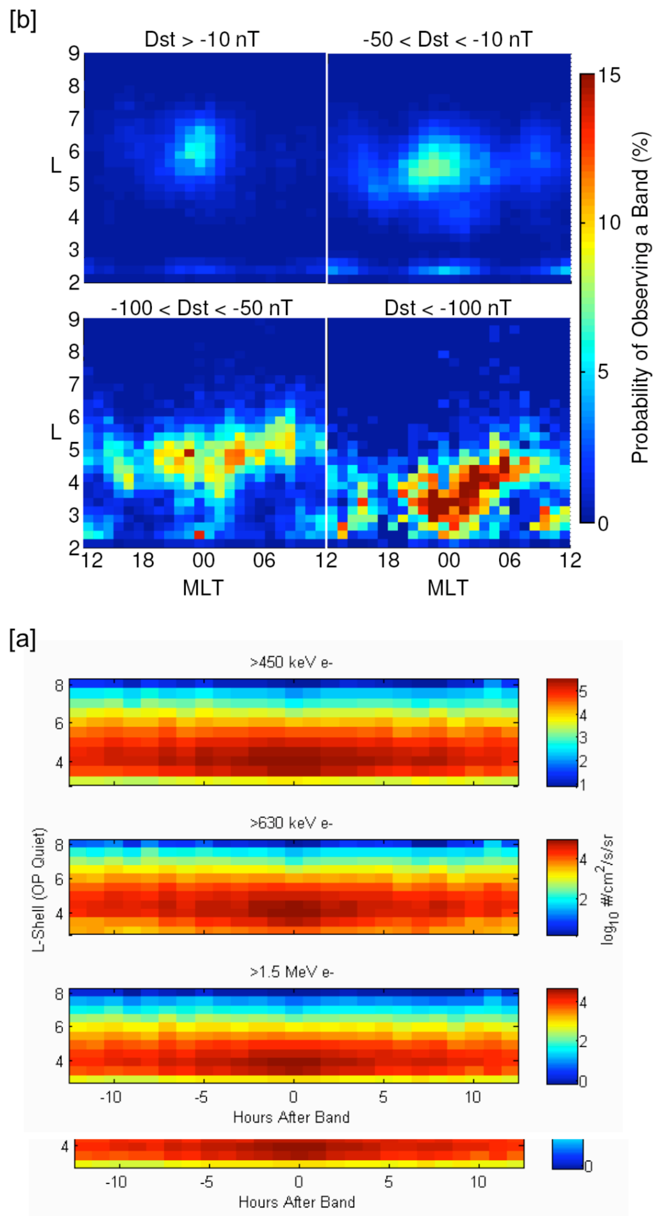

Figure 2. [a] Superposed epoch analysis of high altitude HEO3 fluxes taken during observations of precipitation bands at SAMPEX altitudes.
[b] Spatial occurrence of precipitation bands in L versus MLT for four different levels of magnetic activity defined using D_{ST} ranges.

Figure 2a shows the spatial distribution of precipitation bands, observed by SAMPEX, in L versus MLT at four different levels of magnetic activity specified by D_{ST}. During the quite and low activity periods the SAMPEX precipitation bands are localized at the higher L values (≥5) on the night side, consistent with the early observations (Vampola, 1977). During moderate and high activity levels the occurrence of precipitation bands expands to earlier and later local times and to lower L values. Figure 2b shows a superposed epoch analysis of HEO3 observations, taken during the same time frame that SAMPEX precipitation bands occurred, which shows that the high altitude fluxes were relatively unperturbed on average. These more recent observations are consistent with Vampola's [1977] earlier conclusion.

The question is, can we really explain all these observations where evidence of strong pitch angle scattering is often observed, out to the trapping boundary, at low altitudes while little response occurs closer to the equator? How do we provide a quantitative explanation of the scattering and loss? Is the whole electron angular distribution isotropized or only a portion of it consisting of the electrons with pitch angles near the loss cone? How can we tell? The questions beg for an observational mission to answer them once and for all time. We outline the requirements for a possible satellite mission below.

Satellite Mission Requirements

What are the requirements for a satellite mission to examine the electron precipitation causes and their characterization? Taking the historical and most current observations as our guide, it is clear that we need a mission to study the electron loss cone and near loss cone angular distributions. But we need to do this close up and not from the magnetic equator where it is difficult to resolve the loss cone with modest instrumentation and obtain statistically significant electron flux samples. Selesnick et al. [2003] showed the great potential of measurements of both the drift and bounce loss cones for understanding radiation belt electron loss, but, due to the orbit and instrument limitations of SAMPEX, they were required to make several crucial assumptions that could not be verified. Additionally, we would prefer to not have a sun synchronous orbit so that local time sampling can be achieved at all L values to characterize the MLT dependence of the electron scattering for comparison with possible mechanisms (e.g., EMIC versus CHORUS scattering) and previous observations such as those in Fig. 2a.

A simple satellite configuration would be a spinning satellite with its spin axis perpendicular to the magnetic meridian plane to provide the best viewing of the pitch angle distributions for particle sensors mounted perpendicular to the spin axis. The vehicle could have solar arrays on all sides or be much like the S3-2, S3-3 and POLAR satellites that had arrays on the sides and one end. The satellite could be reoriented using magnetic torquing coils to maintain the sun on the arrays and the spin axis perpendicular to the meridian plane of the field. Examples of such vehicles are the USAF S3-2 and S3-3 satellites, which used torque coils, and NASA's POLAR satellite, which used a gas system, for reorienting their spin axes. The spacecraft spin rate should be optimized to give relatively rapid sampling of the complete 2-D angular distributions. Roughly a 5 second spin period would be a good compromise.

To cover all the L values involved a satellite needs to have a high inclination orbit that passes in latitude from above the poleward edge of the radiation belt, through the outer radiation zone and down through the slot region (i.e., from 12-15 > L > 2). At the same time, the orbital altitude of the spacecraft must be high enough to sample pitch angles that are sufficiently outside the bounce and drift loss cones so as to obtain a good reading of the pitch angle distribution shape away from the loss cone. Simultaneously it must be at low enough altitude that the loss cone is wide enough to be resolved by relatively simple particle instruments. As an example, for a mission with an altitude of ~8000 km the local pitch angle corresponding to the loss cone is ~30°-40°. Such a loss cone would be mappable with simple particle instruments such as those to be flown on RBSP. The loss cone would represent 30-45% of the local pitch angle coverage. Thus there would be a sensitive measurement of the particle distributions approaching and into the loss cone. Such a measurement would also resolve the drift and bounce loss cones most of the time, enabling observation of fast (bounce timescales) and moderate (drift timescales) loss processes.

However, the satellite orbit need not be circular. A high inclination elliptical orbit with an apogee of 8000 km or slightly greater would also work, especially if the orbit precesses (as it most likely will) such that a range of altitudes are obtained at each L value traversed over the mission life. Such orbits can be achieved by piggybacking as a secondary payload on a launch with excess capability, for example using an ESPA ring.

In addition to energetic electron sensors for measuring the electron pitch angle distributions over a 20 to 2000 keV energy range, the satellite should also carry a good plasma electron/ion sensor, that performs well in penetrating electron fluxes, energetic ion spectrometers to measure, as a minimum, the protons from 10's to 1000's of keV, a science quality magnetometer, a plasma wave experiment and a plasma density measurement. The wave experiment should provide at least a two-axis measurement of wave E and three-axis measurement of wave B over the full VLF range to cover from ion cyclotron frequencies to beyond the electron gyrofrequency. The magnetometer needs to sample at a high enough rates to provide overlap with the wave experiment on the low frequency end, cover the LF, ULF, and ELF frequencies and provide field "DC" vectors at rates sufficient for the particle and plasma sensors to obtain good pitch angle resolution. Such a compliment of instruments could provide all the measurements necessary to investigate the electron pitch angle diffusion near the loss cone and determine whether it is a local or remote (high on the field line) process. The instruments will also provide measurements of the background plasma conditions necessary to the theory and modeling needed to interpret the electron observations. The wave measurements, of course, are necessary to confirm the existence or lack thereof of local particle scattering near and just above the loss cone. The proton measurements identify ion precipitation related to EMIC generation and ring current injection and penetration to low L values that also play a role in electron losses, such as the enhanced field curvature related scattering noted above.

As secondary science, such a mission would be able to investigate the question of how the inner zone proton belt responds to losses from atmospheric inflation during solar activity and then refills, and how solar particles are entrapped to become an extension of the inner zone to higher altitudes and then dumped during storm activity. In particular, the mechanisms of trapped proton diffusion to refill particles lost during an atmospheric inflation event are largely unknown. Selesnick et al. [2007] omitted pitch-angle scattering entirely from their long-term theoretical simulation of the inner belt, while Looper et al., [2005] showed that some kind of diffusion refills the low altitude extent of the belt (after a storm) over a period of months. Unknown diffusion mechanisms observable from low altitude likely have implications for redistribution of trapped protons at higher altitude, which, in turn, controls the lifetime of protons throughout the inner belt.

No formal costing and mass estimates can be made without expending funds and more time than was available for generating this white paper. However, one can make a reasonable assessment that the mission proposed falls in to the small mission (SMEX like) category for both cost and mass. The cost can be constrained by using copies of sensors that were developed for other missions such as RBSP and THEMIS. The mass is constrained by limiting the number of sensors to a basic set just sufficient to make the measurements required to do the science.

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Enhancement of POES Instruments to Provide Better Space Weather Electron Data

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The NOAA POES platform makes critical measurements of the space environment that are used to support operational programs that need space environment data for anomaly analyses and to develop environmental specifications that inform designs and technology development. However, the primary focus of POES sensors has been on energetic proton fluxes, primarily to monitor solar particle events, and the auroral energy input for monitoring high latitude ionospheric effects. These data have also been used by the science community to study ring current effects and particle precipitation (Sørbø, et al., 2009 is an example). The POES electron observations are very limited and have not been sufficient to support anomaly investigations of possible internal charging issues that have arisen for low to mid altitude spacecraft nor to do significant science analyses related to magnetospheric processes.

An enhancement of the POES electron sensor capabilities would help not only meet the needs of the operational community for continuous data and characterization of the radiation environment for low to mid altitude orbit missions, but would also provide another resource for the science community. From the science perspective there is great interest in determining the energetic (40-2000 keV) electron loss rates as part of understanding the balance between electron acceleration and losses and our attempt to model the processes involved. The short missions that NASA flies provide much of the basic science data for initial model development but do not provide that data durations that make it possible to test, inform, and transition the models of the magnetospheric processes to operational capability.

We would suggest that NOAA seriously consider flying an electron sensor that measures the precipitating and trapped electron fluxes in the 40-2000 keV energy range on a continuous basis to fulfill the operational and science needs noted above.

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Transition Region Exploration (TREx) Mission

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Understanding the transport, acceleration and losses of energetic electrons in the radiation belts is one strong focus of magnetospheric science. There is evidence that argues for in situ acceleration processes, involving wave particle interactions, that generate in a peak in electron phase space density (PSD) in the L region of 5-6 (Green and Kivelson, 2004; Chen et al., 2008). Green and Kivelson [2004] used a single sensor on the POLAR satellite to examine the energetic electron PSD radial profiles to determine whether the shapes were consistent with radial diffusion or not. They found that that the data are best explained by models that require acceleration of an internal source of electrons near L* ~ 5. They also suggested that outward radial diffusion from a PSD peak near L* ~ 5 could explain the observed correspondence between flux enhancements at geostationary orbit and increases in ULF wave power. However their radial profiles were constrained to small pitch angles (large K values) in order to obtain radial profiles over a sufficient range of L* for constant first and second adiabatic invariants.

Chen et al. [2008] used data collected by multiple satellites in the magnetosphere at different distances from the Earth and identified frequent and persistent peaks in equatorial electron PSD near geosynchronous orbit. They argued that their results provided "unambiguous" evidence for local wave–particle acceleration, consistent with the Green and Kivelson [2004] results. However, as in all such studies there is difficulty in intercalibrating the different sensors and establishing the accuracy of the magnetic field models for computing the phase space densities for constant first and second adiabatic invariants. Chen et al. used two data sets from GPS and GEO that did not have magnetometer data for comparing against field model values (GOES magnetometer data from different longitudes at GEO were available). POLAR magnetometer data could be used. However, the highest L* points may or may not have been taken on closed drift shells. It is hard to know since a range of K values was not examined (see below).

Fennell and Roeder [2008] used data from the SCATHA satellite whose near equatorial orbit spanned the 5.2 ≤L*≤ 7.3 region to examine the storm time electron response over that range of L* for a wide range of constant first and second adiabatic invariant values (M=200-2500 MeV/G and K=0.05-0.65 Re√G). They found that the PSD radial profiles showed a range of features from peaked in L* at small K and M during the pre-storm period to those in the late storm recovery phase, that were flat, had negative slopes for small K and had peaks in the L*= 5.2–6.5 range for intermediate to large K. The results implied that radial diffusion was a reasonable explanation of the near-equatorial post-storm PSD enhancements for L*>5.2 but that either significant electron pitch angle transport, losses, and/or acceleration of off-equatorial mirroring electrons by waves played an important role in the evolution of off- equator PSD profiles during storm recovery. Like Green and Kivelson [2004], Fennell and Roeder [2008] used data from a single instrument and spacecraft. Like the others, though, they had to rely on field models to assess the phase space densities at constant first and second adiabatic invariants but they were able to intercompare the measured magnetic field values to the field model outputs along the satellite trajectory (as was Green and Kivelson [2004]), which is an important constraint for any study of the processes involved. In fact, one thing that was noted by Fennell and Roeder [2008] was that the PSD profiles had different shapes for different K's and that at the larger K values some of the profiles had very sharp negative gradients which could be consistent with the particles not being on closed drift shells beyond some L*. This would mean that the model fields used to assess K and L*, which predicted the observations were taken on closed drift shells, did not match the real conditions.

What were missing in all the studies noted above were good plasma wave measurements. Because they were lacking, none of the noted investigations could actually point to the existence of waves required for any in situ acceleration of the particles during the events studied. The wave smoking gun was missing and what remained were inferences from an incomplete data set. It is clear that what is needed to definitively determine whether relativistic electrons are accelerated, in situ, from a seed population by waves, is a mission similar to the SCATHA mission that covers the critical L* range from 4.5<L*<8 that is properly instrumented to make all the critical measurements. We note that the RBSP mission, which has an apogee of 5.6 Re may not provide a definitive answer because it may not reach large enough L* values to observe the PSD peaks noted in the discussion above.

As secondary science, it should be noted that a mission, as described below, could provide the kinds of in situ plasma boundary condition data needed for ring current modeling. It allows one to set the boundary condition above geosynchronous, if desired and to track the plasma conditions down towards the plasmapause boundary during quiet times and well interior to geosynchronous during disturbed times.

Satellite Mission Requirements

A simple low cost mission could be configured to determine whether indeed acceleration of an internal source of electrons is required to explain the PSD profiles in the 4.5<L*<8 region for a wide range of M and K, with K~0.0 – 1.0 a goal. The critical measurements needed are as follows. Electron sensor(s) are required that measure the flux and angular distributions of 20-3000 keV electrons with good statistics and good angular resolution. E and B wave measurements the cover the frequency range from the ion cyclotron frequency (if possible) to beyond the electron gyro frequency, at L*=4.5, which, as a minimum, should be 2-axes in E and 3-axes in B. A measurement of the DC magnetic field vector with a sample rate sufficient to overlap the wave sensor frequency range at the low end and sufficient to provide detailed particle pitch angle determinations and B-field variations is required. A plasma electron/ion sensor is needed to provide the background plasma conditions for the waves, the seed electrons for wave-particle acceleration, and the ions for estimating warm plasma density and measuring the low energy end of the ring current. A proton spectrometer is needed to measure the bulk of the proton distribution (30 keV to a few MeV) that participates in EMIC scattering during storm times and carries the bulk of the ring current energy at moderate to quiet times. Finally, a plasma density measurement is needed with sensitivity from as low as reasonable to >100 cm^{-3}. As an option, a ring current composition measurement in the 10 - 200 keV/ion range could be considered, resources permitting.

To obtain the L* and K ranges indicated requires a near equatorial orbit with a perigee and apogee of ~4.4 and ~8.5 respectively with inclination ≤ 5°. This can be attained by piggybacking on a launch to geotransfer or geosynchronous orbit and then using a small thruster to achieve final orbit configuration. (Note: such an orbit has a period slightly less than 24 hours such that the apogee will "drift" in longitude about 10°/day.) The least expensive configuration, from the sensor perspective, is for the vehicle to be a spinner with the spin axis in the orbit plane. In this way pitch angle distributions can be obtained by mounting the sensors such that their fields of view are perpendicular to the spin axis, much like those were on SCATHA, CRRES and those on RBSP. The sensors themselves can be copies of those being flown on RBSP or THEMIS, as appropriate. Attitude maintenance could be done using a cold gas system like that on RBSP or POLAR or small plasma thrusters like those used on geosynchronous commercial communication satellites. Plasma thrusters could even be used to achieve the final orbit configuration as has be done by recent geosynchronous missions.

This mission is between a small and medium sized mission depending on whether it is a secondary payload as noted above or requires its own launch.

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Interaction of the Solar Wind with a Partially Magnetized Planet

This topic proposes a spacecraft experiment that deals with our nearest neighbor planet, Mars, and its interaction with the space environment. NASA has been directing efforts toward this planet with the future hopes of human exploration. Mars does pose many challenges to humans, one of which has to do with radiation from plasma. Unlike the Earth, Mars does not possess a protective internal magnetic field; however, it does contain remnant magnetic field in its crust. This crustal magnetic field is localized and does not cover the entire planet. The regions of the crustal magnetic field do create pockets of shielded space and act like mini-magnetospheres.

We know that Mars interacts with the solar wind. This interaction causes most of the solar wind to be deflected around the planet, but a portion of the solar wind can penetrate the ionosphere, and under some solar wind conditions, reach all the way down to the surface of the planet. In order for Mars to stand off the solar wind a portion of the plasma must form a complex current system around Mars, creating an induced magnetosphere to aid in shielding the planet.

The plasma interaction between an induced magnetosphere and the solar wind has not been studied in detail, nor has the plasma interaction between the induced magnetic field and the crustal magnetic field. What is the 3-dimensional distribution of the interaction of Mars with the solar wind and what is this interaction with crustal magnetism? In particular, what is the 3-dimensional interaction between the solar wind and the planet's bow shock? What is the nature of the current system which causes the standoff of the solar wind, and how does this system break down in times of strong solar wind? These questions must be addressed since the protective shielding of the Martian magnetic field will play an important role in its exploration by humans.

Previous spacecraft have sampled the plasma environment in the geospace around Mars mostly in 2-dimensions. They have discovered that the interaction of the planet with the solar wind takes the form an induced magnetosphere interaction; however, crustal anomalies complicate the picture. Previous instrumentation at the planet has concentrated on planetary measurements of mass escape and probing crustal magnetic fields. The experiments have been geological in nature, and therefore the required instrumentation has not been available to examine the 3-dimensional plasma flow at points around the planet, from the solar wind through the bow shock, into a maze of plasma creating a current flow to form the induced magnetic field, and out from the planet's tail.

In order to accomplish this feat, it is suggested that a spacecraft mission to Mars is required. On this spacecraft, measurements must be made with state-of-the-art instrumentation on a spacecraft platform which has been designed for plasma measurements. A spinning spacecraft is most desirable to ensure stability and provide the opportunity of sampling plasma in the same regions of space using different instrumental components, reducing measurement error.

Care should be taken not to include items which could complicate measurements, such as gridded elevation analyzers when measuring electrons (since the grids are a source of secondary electrons). A suggested complement of instruments for a payload is as follows:

Active potential control - control the spacecraft potential to allow lower energy plasmas to be measured.

Electric fields - determine AC and DC electric fields at a fast temporal rate.

Electron detector - determine the general 3-dimensional distribution of electrons at a fast temporal rate.

Ion mass analyzer - determine the proportion of ion species and ion charge at a slower temporal rate.

Langmuir probe - determine the local density and spacecraft charge at a fast temporal rate.

Magnetometer - determine AC and DC magnetic fields at a fast temporal rate.

Total ion detector - determine the general 3-dimensional distribution of ions at a fast temporal rate.

Here, the terms fast and slow referring to temporal rates are dependent on the rate of appropriateness to diagnosis the phenomena being measured.

The orbit of the spacecraft should be elliptical with a pericenter altitude of 250 km and apocenter altitude of about 15,000 km. The orbital plane should be about parallel to the polar axis of the Earth and take about two Earth years to precess (the measurement plane should differ enough to allow for sampling during Mars eclipse). The semi-major axis of the ellipse should take about an Earth year to precess along the orbital plane. The primary mission should be at least 5 Earth years long.

White Paper: Particle Acceleration and Entry of Solar Wind Energy into the Magnetosphere

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1. Recommendation

It is recommended that the Solar and Space Physics Decadal Survey include as one of its goals, "understanding the physics and influence of particle acceleration in the magnetospheric cusp."

The remainder of the white paper outlines the variety of magnetospheric scientific questions that can be answered through study of the particle acceleration within the cusp.

2. Particle Acceleration in the Cusp

Cusp physics contribute to both our understanding of focus areas solar wind-magnetospheric interactions as well as ionosphere-magnetospheric interaction. The cusp provides the most direct entry for solar wind plasma and energy into the magnetosphere. The exterior cusp has also been shown to be an efficient producer of energetic ion and electron populations up to several hundred keV (Chen et al., 1998). A magnetic connection between the cusp and many other regions in geospace allows it to feed these areas with energetic particles. Although particle acceleration to hundreds of keV in the exterior cusp was originally a disputed conclusion from the Polar mission, it has become more and more accepted in recent years through modeling and observations (Otto et al., 2007; Walsh et al, 2010; Nykyri et al., 2010).

Advancing cusp and particle acceleration research has widespread applications and will also help answer outstanding challenges from the previous study looking for progress in "understanding the space environments of Earth and other solar system bodies and their dynamical response to external and internal influences." As plasma of solar wind origin (He^{+2}, O^{+6}) as well as ionospheric (O^{+}) plasma enters the exterior cusp, it's frequently undergoes efficient acceleration (Chen and Fritz, 2001). This was convincingly demonstrated in a fortuitous set observations by the ACE spacecraft and the Polar satellite during a solar event in May 2-3, 1998, in which the "freezing-in temperature" of ion charge states caused the average charge state of iron ions to vary from 6 to 16 (Gloeckler et al., 1999). This variation effectively provided a time tag for the propagation of the solar wind plasma from the L1 location of ACE to the position of Polar in the magnetosphere inside the dayside cusp. Perry et al. (2000) demonstrated that the solar wind plasma had direct rapid entry into the cusps. Figure 1 demonstrates the tracking of the ACE and Polar measurements of the Fe charge states when Polar was at apogee in the dayside cusp. The Polar measurements have been delayed using the measured solar wind speed. In the third interval of Figure 1 the Polar data were summed for four half-hour intervals beginning at 1900 UT and 2300UT on May 2, 1998 and 0200 UT and 1400 UT on May 3, 1998 and a comparison of the phase space density at ACE and Polar was determined for each interval. The first of these which is quite similar to the other three is displayed in Figure 2. One will notice that in addition to the thermalization that has occurred to the plasma distribution, there

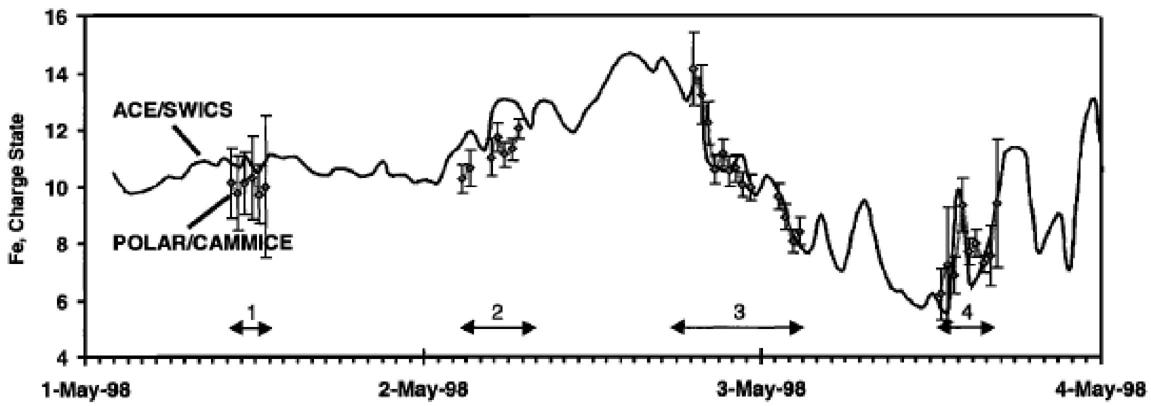

Figure 1. Average Fe charge state measured by ACE/SWICS at L1 between May 1 to 3, 1998. Times have been corrected for the propagation delay from L1 based on the observed solar wind flow velocity. Equivalent data from the Polar/CAMMICE instrument is shown for four cusp traversals during this period. (Figure 2 from Perry et al., 2000)

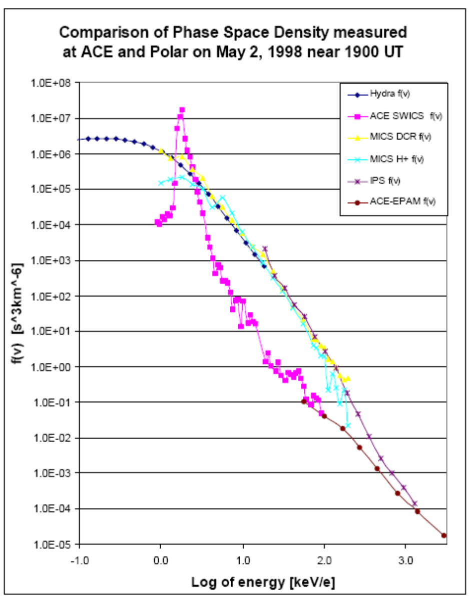

Figure 2. The phase space density of the total ion population determined by the SWICS and EPAM instruments at ACE and by the HYDRA, MICS, and IPS instruments on Polar, as a function of energy per charge. The two populations correspond to a plasma with an average Fe charge state of +15. (Figure 2 from Fritz et al., 2003)

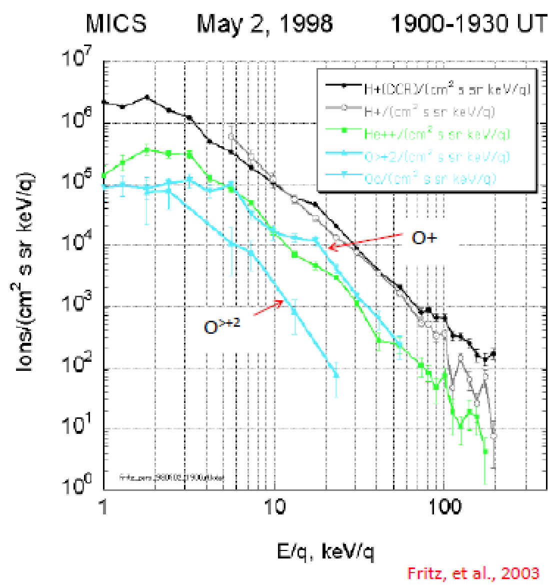

Figure 3. The energy spectrum of flux versus energy per charge of the four major ion species determined for the interval from 19:00UT to 19:30UT on 2 May 1998. (Figure 7 from Fritz et al., 2003)

has been a significant energization in the range from less than 10 keV to greater than 100 keV which is the energy associated with the ring current. When the energy spectra of these ions is examined as a function of their composition a surprising result is found in which the energization that has occurred in association with their crossing of the bow shock and entry into the cusp a second population of oxygen ions has been added to the mix. The second population is O^+ which must come from the ionosphere and these ions have been energized to 10s and 100 of keV right along with the shocked solar wind ions He^{+2} and $O^{>+2}$ (most probably O^{+6}) to the same spectral form. It is clear that there are acceleration mechanisms operating in the cusp to energize ions to ring current energies and above.

There are a variety of questions that can be answered through investigating this acceleration mechanism. How is solar wind energy deposited into the magnetosphere? What is the source of energetic particles in the plasma sheet? How does cusp acceleration and transport of energetic particles from the cusp change with solar wind conditions? What is the source of the energetic particle layer on the magnetopause? How significant are the contributions of energetic particles from the cusp to the radiation belt?

3. Plasma Sheet

Understanding the origin of the energetic electron population within the plasma sheet remains an open question and has implications for radiation belt filling. Understanding acceleration in the cusp will help solve this problem.

The magnetic field lines threading the cusp form the magnetopause, so particles accelerated in the cusp and traveling along the field lines will form an energetic particle layer painting the magnetopause. Many reports have confirmed the existence of such an energetic particle layer just outside the magnetopause along the flanks of the magnetosphere (eg, Meng and Anderson, 1970). Sarris et al. (1976) reported that bursts of energetic particles of non-thermal origin both within and outside of the magnetotail are a semipermanent feature with energies ranging beyond 4.5 MeV for ions and 1 MeV for electrons. Baker and Stone (1977) observed a layer of energetic electrons (E>200 keV) to be persistently present (97% of crossing, >70% of the time) in the range $-10\ RE > X_{SM} > -40$ RE. The electrons were streaming tailward along the local magnetosheath field lines. This layer appears to completely envelop the magnetopause and has a roughly annular cross-section. Williams et al. (1985) and Mitchell et al. (1987) analyzed magnetopause crossings of the ISEE-1 satellite along the dusk and dawn flanks and found that the occurrence and width of fluxes of > 25 keV ions which they ascribe to a boundary layer increased with increasing distance away from the subsolar region becoming a tailward flow with the particles appearing on both sides of the magnetopause.

Parts of the energized population along the magnetopause will subsequently gain access into the plasma sheet and magnetotail along the flanks due to gradient drift entry (Olson and Pfitzer, 1985; Klida and Fritz, 2009). Ions would drift in on the duskside and electrons on the dawnside. In 1999, Sibeck et al. (1999) stated that gradient drift entry was "the least explored of all proposed interactions between solar origin particles and the Earth's magnetic field." Understanding the role of energetic particle entry in general, and particularly the entry of particles accelerated up to hundreds of keV in the cusp into the nightside plasma sheet remains an unanswered question and could have influence for local currents and electric fields to the extent that these electrons could contribute significantly to the cross-tail current.

4. Radiation Belt

In addition to gradient drift entry, energetic electron and ions (in particular) have access to the inner equatorial magnetosphere along trajectories known as the "Shabansky orbit" illustrated in Figure 4 (Fritz, 2000). Drift trajectories of this type are due to the compressed nature of the sub-solar magnetopause and the creation of minima in the field strength along the sub-solar magnetic field away from the equator. Such particles have access to the geostationary orbit in the nightside equatorial magnetosphere. With such a

The particle trajectory known as the Shabansky orbit

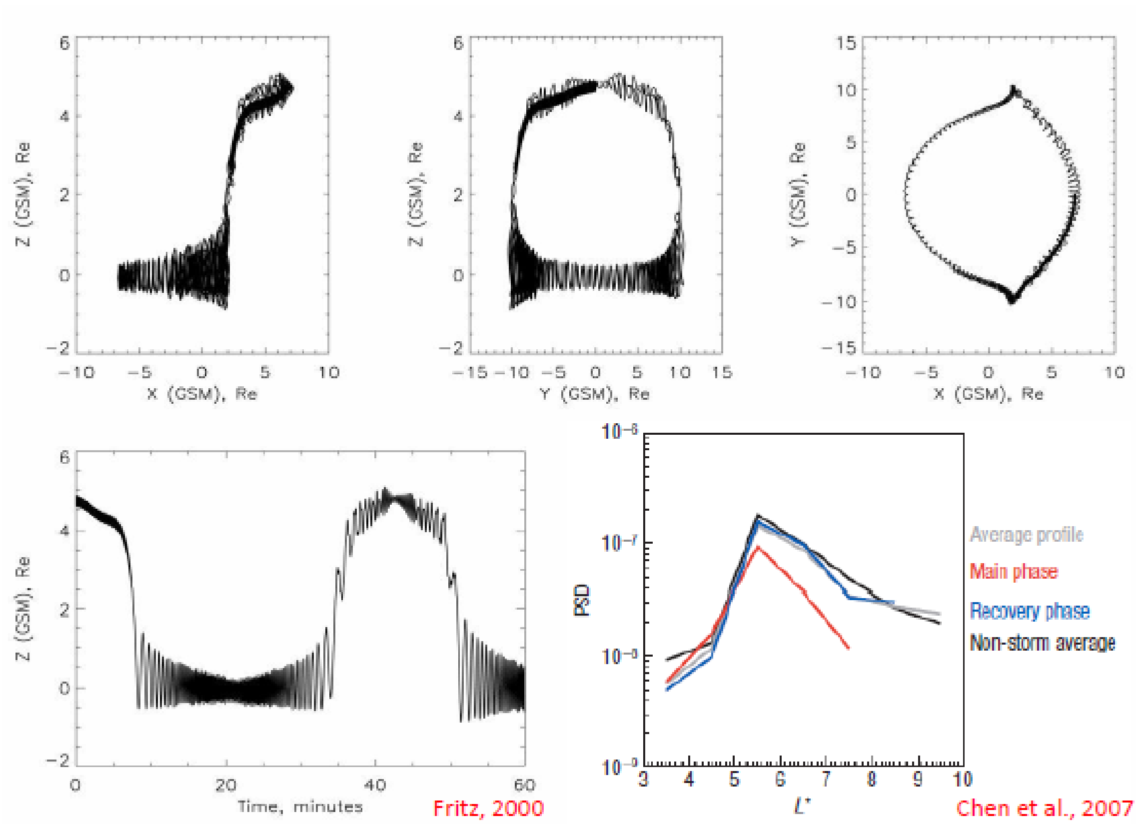

Figure 4. The trajectory of a 200 keV proton is shown in which the particle's Lorentz motion is determined with an adaptive fourth-order Runge-Kutta method in which the particle's orbit is traced in a magnetic field model based on the IGRF internal field and the Tyganenko 96 external field model (Fritz, 2000). The inset in the lower right shows a superposed epoch analysis that bins PSD as a function of L and geomagnetic storm phase during a two year period (2001–2002). Here the first invariant μ =2,083 MeV G^{-1}, the second invariant K =0.03 $G^{1/2}$RE and the unit of PSD is (c^3 MeV^{-3} cm^{-3}). The radial PSD distributions for all geomagnetic conditions averaged over available data from the two year period 2001–2002 (grey), during storm main phases (red), during storm recovery phases (blue) and during times when Dst indicated no geomagnetic storm activity (black). Here L has a bin size of 1 and the central-point value of the first bin is 3.5 (Chen et al., 2007).

source of energetic particles one would expect there to be a peak in the phase space density at this location. The inset in Figure 4 shows just such a peak in the phase space density (Chen et al., 2007). When the phase space densities are compared directly as shown in Figure 5, the values in the cusp dominate. A comparison of the energy spectrum taken during an energetic particle event in the cusp with the spectrum of energetic ions taken at the geostationary orbit is shown in Figure 6 demonstrating the similarity of the spectra.

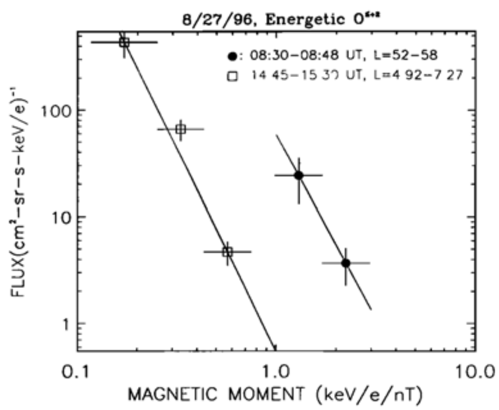

Figure 5. Comparison of the magnetic moment spectra of the energetic $O^{<+2}$ at the cusp (solid circles) with that at the ring current (open squares) Chen and Fritz, 2001

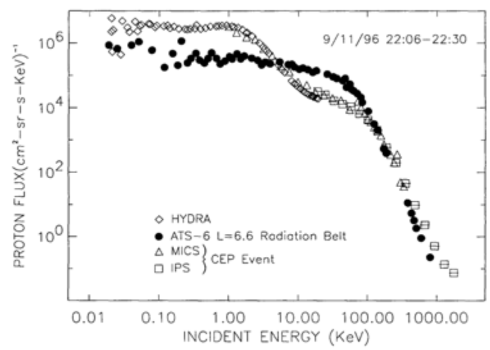

Figure 6. Composite figure showing the proton energy spectrum measured by the Polar satellite in the altitude cusp during a Cusp Energetic Particle (CEP) event and by the ATS-6 satellite at the geostationary orbit on the nightside of the Earth. (Fritz et al., 2000)

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Stereo Magnetospheric Imaging (SMI) Mission

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Science Target: Understand global magnetospheric processes such as plasma entry into the dayside magnetosphere, across the Earth's bow shock, plasma processing in the magnetospheric cusps, and plasma sheet disruption in the tail.

Method: The SMI mission consists of two identically instrumented spacecraft with neutral atom imagers covering energies from 0.01 eV to 20 keV. The spacecraft are placed at the Lunar L4 and L5 vantage points to provide stereoscopic imaging of the magnetosphere and magnetosheath for most of the lunar month. An example image (from the IBEX spacecraft) showing major magnetospheric boundaries and regions is shown in Figure 1.

Description:

The IMAGE spacecraft provided the first neutral atom images of the inner magnetosphere and revolutionized the understanding of inner magnetospheric processes. The neutral atom imagers on this spacecraft demonstrated that inner magnetospheric processes in the ring current could be discerned. In addition, imaging of ion outflow from the ionosphere as observed by the low energy neutral atom imager [Moore et al., 2000] revealed the global nature of ion outflow during, for instance, substorm recovery [Fuselier et al., 2009].

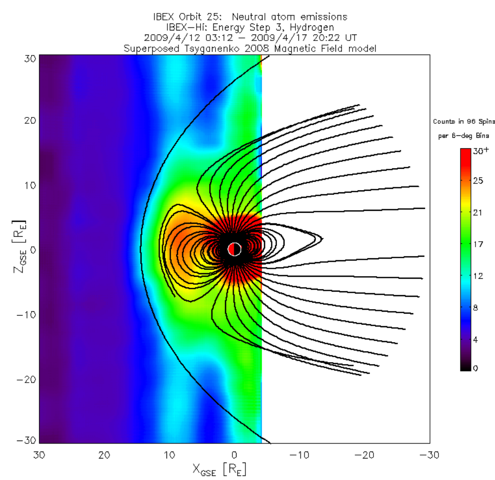

Figure 1: 1 keV Hydrogen ENA image of the magnetosphere from the IBEX spacecraft. The bow shock northern cusp and subsolar magnetopause are revealed in the light of neutral atoms.

The IMAGE mission was followed by the TWINS explorer mission of opportunity. These two neutral atom imagers on near-polar orbiting spacecraft demonstrated the advantages of stereo imaging. Again, the focus was on the inner magnetosphere (ring current and plasma sheet).

Both IMAGE and TWINS neutral atom imagers focused on the relatively bright neutral atom fluxes from ionospheric outflow and the inner magnetosphere ring current. The neutral atoms imagers on the IBEX explorer mission have considerably larger geometric factors than previous instruments (because they image the relatively weak fluxes from the heliosphere). As a result, this mission can image neutral fluxes considerably further from the Earth than was possible with the IMAGE or TWINS mission. Figure 1 is a 1 keV neutral atom image from the IBEX-Hi camera and demonstrates the sensitivity of the imagers. Neutrals are imaged from charge exchange of solar wind plasma in the cusp, dayside magnetopause, within the magnetosheath, and at the bow shock. These are the first images of the magnetosheath and cusp [Fuselier et al., 2010; Petrinec et al., 2010]. In addition, IBEX has imaged the plasma sheet and magnetotail out to radial distances of >20 R_E from the Earth [McComas et al., 2010].

These exploratory imaging missions have been extremely successful and discovered new unexpected phenomena. The IBEX ribbon at the outer reaches of the solar system is just one example. Performing the next step and proceeding from a one spacecraft mission to a two spacecraft mission such as SMI represents a natural progression. SMI will combine the proven advantages of TWINS and IBEX to explore the Earth's magnetosphere, the Moon and its interaction with the magnetosphere, and the heliosphere in one mission.

The SMI mission will answer the following science questions (objectives):

1. What is the dynamic, coupled response of the Earth's bow shock, magnetosheath, and magnetopause to solar wind variability?
2. What is the fate of solar wind and ionospheric plasma in the cusp? How does this fate depend on solar wind conditions?
3. How does the Earth's magnetotail respond globally to different solar wind input?
4. How does the Moon affect the Earth's magnetosphere when it is in the magnetotail?

In addition, during part of the orbit, the SMI mission will be well positioned to extend the IBEX observations of neutral atoms from the Heliosphere and Interstellar Neutrals from interplanetary space. Therefore, the additional, cross-cutting science questions are:

5. What is the long-term stability of the Ribbon of enhanced heliospheric neutral atom emissions discovered by IBEX?
6. How do the characteristics of the Ribbon and more globally distributed fluxes change smoothly and continuously or abruptly above 6 keV (i.e., above the high energy cutoff of the IBEX neutral atom cameras)?
7. What are the concentrations of neon and other minor species in the interstellar wind and how are these concentrations related to processing of interstellar matter in stars?

Mission Description:

Two identical sun-pointing spinning spacecraft are placed at the L4 and L5 lunar Lagrange points that lead and trail the Moon. Figure 2 show the spacecraft constellation and the Earth – Moon location during three major observing periods (the location is shown around the Earth, but major observing periods occur each lunar month). For more than half of the lunar month, these two spacecraft provide stereo views of the magnetosphere from the dawn and dusk perspective.

These intervals are used to answer science questions 1 through 3. Part of the lunar month, the spacecraft flank the moon as it passes through the magnetotail. These intervals are used to answer science question #4. Finally, for part of the lunar month, the two spacecraft flank the moon well upstream of the Earth's magnetosphere. These intervals are used to answer questions 5 through 7. The spacecraft are Sun pointing spinners and the ENA cameras are placed 90 degrees off the spin axis and on the opposite side of the spacecraft.

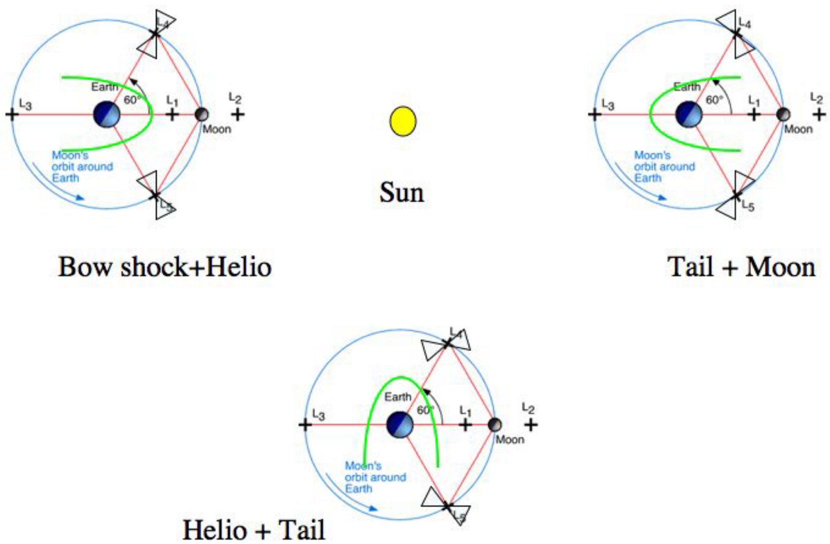

Figure 2: The viewing geometry of the SMI mission allows magnetosphere stereo viewing and heliospheric viewing each lunar month. In less than a half year (because of the scanning capability of the imagers) a full sky view of the heliosphere is obtained, multiple stereo views of the magnetosphere are obtained, and several passes of the moon through the magnetotail are imaged.

Mission classification:

The SMI mission can be accomplished with two simple spacecraft that are launched into lunar L4 and L5 points. The total budget of SMI is of the order of a small-class (250-500M$) mission. The spacecraft are Sun-pointed spinners based on the IBEX spacecraft. Solar arrays will provide power for all spacecraft subsystems and for all instruments. Data will be stored continuously in spacecraft memory and downloaded periodically into the data center. Data downlink will be accomplished through a high-gain antenna and data volume is very modest (both instruments will produce only ~200-400 bps). The spacecraft may be somewhat more complex than the IBEX spacecraft because the imagers may have to perform scans out of the spin plane (by angles as much as ±20°). However, spacecraft mass, based on the IBEX spacecraft with some enhancements, would be approximately 150 kg.

Launch vehicle:

Since the spacecraft are relatively simple, a Taurus-class launcher may be used. The details of the orbit insertion require more study, but it most likely includes using the moon to adjust the orbit, thereby saving fuel and mass.

Spacecraft payload

Sensor	Measurements	Energy	Mass	Power	Number of Sensors
SMI-Lo	**ENA**	**0.01 – 2 keV**	**11 kg**	**7 W**	**1**
SMI-Hi	**ENA**	**0.7 – 20 keV**	**11 kg**	**8 W**	**1**
UV/star sensor	**Geocorona and UV stars**	**Lyman-Alpha**	**1 kg**	**2 W**	**1**
Background Monitor	**Energetic Ions**	**>15 keV**	**200 g**	**0.2 W**	**1**

Observational variables:

The two identical spacecraft with a spin period of 4 rpm will be equipped with **two neutral atom cameras (Lo and Hi)** covering an energy range from 0.01 – 2 keV and from 0.7 – 20 keV. The baseline design for these cameras follows the IBEX-Lo and –Hi sensors. Both SMI-Hi and -Lo would be single pixel cameras with a Field-of-View of ~6°. The sensitivity could be improved beyond that of IBEX, but the science does not require the SMI sensors to be much more sensitive. Like IBEX, the SMI-Lo camera will have the capability of separating masses in order to image neutrals from ionospheric ion outflow and minor species in the interstellar wind.

-For accurate pointing both spacecraft should be equipped with a **UV/star sensor system** to detect UV stars and also the Lyman alpha geocorona (the charge exchange medium for the observed magnetospheric ENAs). This sensor could be very similar to that on IBEX, but would require a better baffle system to narrow the field of view.

The payload should contain a **background monitor** to measure energetic particles that cause background in the ENA detectors. These background measurements are in particular important for heliospheric ENA measurements far outside the magnetosphere. Again, this monitor should require very few resources and could be very similar to the one on IBEX.

The measured quantities are fluxes of ENAs (J_{ENA}) from the helisophere, magnetosphere, magnetotail and the moon representing a line of sight integral along a path *l* of a neutral:

$$J_{ENA}(E,s) = \int J_{ION}(E,s,l) \bullet \sigma(E,s) \bullet n_H(l) \bullet dl$$

where $J_{ION}(E,s,l)$ is the flux of ions of a certain species *s* with an energy *E* at the location *l* . The charge exchange cross section σ(E,s) and the density of neutral hydrogen $n_H(l)$ are commonly known quantities. The sensors measure the ENA flux and the equation is inverted by knowing the ion cross section and neutral hydrogen (geocoronal) density (obtained from the UV sensor).

Expected Results:

Magnetosphere:

- SMI data will build on the IMAGE, TWINS, and IBEX successes. IBEX was the first to make global images of the bow shock, magnetopause, and cusps. SMI will provide the equivalent of TWINS stereo viewing for these outer boundaries.

- SMI will have the time resolution to be able to study the global dynamics of the magnetosphere during and after interplanetary disturbances.

The Moon:

- SMI will return lunar ENA measurement and, more importantly, will investigate the global consequences of the Moon's motion through the magnetotail.

- …

Heliosphere:

- SMI will continue heliospheric ENA measurement with higher time resolution, extend the measurements beyond 6 keV, and because of the larger distance to the magnetosphere make measurements with less interplanetary background.

- SMI will complement IBEX measurements over two to three solar cycles.

Relevance:

SMI will address science issues that are of central importance for the magnetospheric as well as the heliospheric science communities. SMI addresses all three primary objectives that define multi-decadal studies:

- *To understand the changing flow of energy and matter throughout the Sun, Heliosphere, and Planetary Environments.*

SMI will significantly improve our understanding of global magnetospheric processes such as plasma entry on the dayside magnetosphere, the Earth's bow shock, plasma processing in the magnetospheric cusps, and plasma sheet disruption in the tail, as well as in the heliosphere.

- *To explore the fundamental physical processes of space plasma systems.*

SMI will address fundamental physical processes such as charge exchange, plasma entry into planetary magnetospheres, as well as entry of interstellar neutral atoms into the heliosphere. SMI will address the formation of large-scale plasma structure at planetary magnetospheres as well as the interaction with of the solar wind with planetary objects such as the Moon without a magnetic field.

- *To define the origins and societal impacts of variability in the Earth-Sun System.*

SMI is also related to the societal relevance investigation: How do the magnetospheres and solar wind interact with each other? Understanding acceleration and plasma transport are fundamental processes at planetary magnetospheres.

Summary:

SMI will investigate and resolve long-standing questions on the origin and transport of plasma within a planetary magnetosphere, around the Moon, and in the heliosphere. With its observations it will provide an interdisciplinary data set that is interesting for magnetospheric, planetary, and heliospheric science communities. It will address key problems such as plasma entry at the dayside magnetosphere, across the Earth's bow shock, plasma processing in the magnetospheric cusps, and plasma sheet disruption in the tail by providing stereoscopic maps of the key region in the magnetosphere. Moon observations will provide valuable information on how the Moon interacts with the Earth's magnetotail on a global scale. Finally, SMI will provide a high-resolution picture of the 3D heliosphere in the light of energetic neutral atoms.

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White Paper for the 2010 Survey of the Decadal Strategy for Solar and Space Physics

Determination of optical spectra and g-values for negative ions of low-mass atoms and molecules

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Disciplines: SHP – Solar and Heliospheric Physics
SWM – Solar Wind-Magnetosphere Interactions
AIM – Atmosphere-Ionosphere-Magnetosphere Interactions

Abstract

Currently, when studying ions in the field of heliophysics, this is usually done with a focus on positive-charged ions. In the case of the planet Mercury, one has the unique combination of a tenuous atmosphere, more properly called a surface-bounded exosphere, and the existence of an intrinsic planetary magnetosphere. The interaction of the solar wind and the Hermean magnetosphere can cause sputtering at Mercury's surface, thereby releasing regolith material into the exosphere. Through this, and other processes, the exosphere around Mercury is created. Photoelectrons at the surface released via interactions with solar radiation could potentially be captured by just-released particles, such as oxygen which has a high electronegativity. The resulting negatively charged ions would then have their paths altered not only by Mercury's gravity, but also by interactions with the planet's magnetic and electric fields. At the time of this writing, there is a lack of emission spectra and g-values, i.e. light scattering probabilities, for negatively charged ions. Hence, spectrometers can not be used at present to determine the abundance of negatively charged ions in Mercury's exosphere or other solar system bodies with tenuous atmospheres, such as comets. If research into determining the spectra and g-values of negative ions were made available, a new area of research in the field of solar and space physics would be opened up.

Introduction

The constituents of planetary exospheres can be detected remotely using optical techniques. One such method involves making intensity measurements for certain wavelengths known to pertain to an element's or molecule's emission spectrum. In order to determine the density of the measured species, one can use a relation of the form $4\pi N \alpha I/g$, where N is the density, and I the intensity. The g-value in this equation is the probability for light to be scattered by an atom for all directions, i.e. the g-value is a measure of probability for omni-directional emission, and a more detailed description of this parameter can be found in a 2009 paper by Killen et al. [1].

This technique was utilized by the UV airglow spectrometer on Mariner 10 as it examined the planet Mercury [2]. The MASCS instrument on the MESSENGER spacecraft, which has now completed 3 flybys of Mercury and will go into orbit around that planet in March 2011, utilizes the same data analysis principle [3]. Naturally, the application of this technique is not limited to the planet Mercury, and has been applied to the data gathered by various missions, such as the Voyager probes, Cassini-Huygens, and New Horizons.

At present, while there is a wealth of data on the spectra and g-values of neutral and positively ionized species, there is an unfortunate dearth of measurements for negatively charged ions. Some data on negatively charged species is available, such as in the text by Stemmler and Hites, but this is limited to more complex molecules with molecular weights of 94 and above, and thus not highly applicable in the field of space physics [4]. Still, similar techniques to those utilized for the creation of those spectra may be applied to determine the spectra and g-values for negative ions of species that are more commonly detected in solar and space physics missions.

The Giotto spacecraft detected negative ions, including O^- and OH^- among others, at comet Halley in 1986 [5]. For the case of Titan's ionosphere, the Cassini spacecraft was able to detect heavy negative ions, which are interpreted to include several heavy hydrocarbons, as well as the lighter O^- [6]. Note that in both these cases, the instruments used for detecting the negative ions utilized in-situ particle detection techniques, namely electrostatic analyzers. This paper focuses on expanding our capability of detecting negative ions in space environments through the use of optical techniques, which could thus potentially enable remote sensing of negative ions, assuming that their spectral lines do not coincide with those of other species. Such a technique could potentially be applicable for ground-based observations as well, so long as the negative ion emission lines coincide with the Sun's Fraunhofer lines, though choosing the proper viewing conditions can alleviate this concern by cleverly utilizing the Doppler shift effect [7].

Thus, we recommend that funding be made available for laboratory and theoretical research to determine the spectra and g-values of negative ions, such as O^- for example. With the resulting data, it may prove possible to utilize currently active space flight spectrometers to search for negative ion constituents in the exospheres of the instruments' respective planetary or other astronomical targets. Development of new instruments can then begin with the express purpose of looking for the heretofore largely-ignored negatively charged constituents of planetary exospheres.

The case for Mercury

Mariner 10 completed three flybys of Mercury, and proved that there is great scientific insight to be gained from studying this planet [8]. The first Mariner 10 flyby of Mercury found evidence of a planetary magnetosphere, which ignited new interest in the study of this previously neglected planet [9]. As Siscoe pointed out, the study of other planets helps us to better understand our own planet. This becomes especially true when a particular type of process is more pronounced or less encumbered with complex interactions with other processes compared to the case at Earth. Mercury's magnetosphere, out of all the others in our solar system, is the most like Earth's, but its smaller size and lack of a dense atmosphere make it an excellent test case for studying magnetospheres and perfecting computer models thereof [10].

One of the processes that can be responsible for releasing atoms and molecules from Mercury's surface into the exosphere is ion sputtering. Sputtering refers to the process where a particle, often referred to as the projectile, impacts on a target surface with sufficient energy to cause a cascade of collisions. The resulting transfers of momentum end up giving some of the surface's constituent particles a trajectory and enough kinetic energy to overcome the binding energy of the target material and thus are ejected from the target, an example of this is shown in Figure 1 below. In addition to momentum transfer, there is another mechanism known as potential sputtering which can be quite efficient at releasing particles from the surface as well.

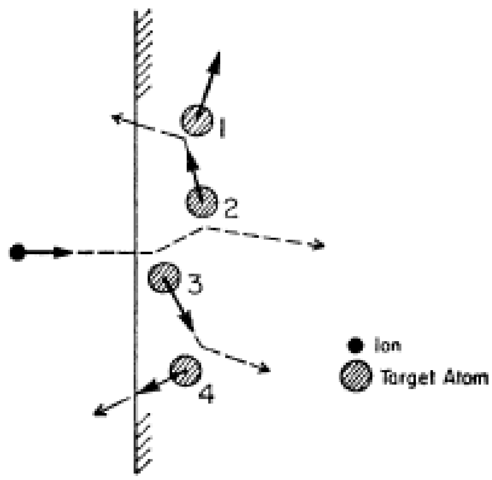

Figure 1: Ion sputtering schematic [11]

At Mercury, the intrinsic magnetic and electric fields provides an acceleration mechanism which guides ions, whether they originated from the solar wind or from Mercury's surface via some previous release process, to the surface and those with sufficient energy then cause sputtering when they impact.

The solar system is filled with micrometeoroid debris which can impact on larger bodies such as planets. At Mercury, the lack of a dense atmosphere allows micrometeoroids to impact at a fairly constant rate. Larger meteoroids impact at lower frequencies and are thus often considered fairly negligible at Mercury. Micrometeoroids with a radius in the range of 10^{-8} to 10^{-1} m are considered to be of the greatest importance [12]. When these micrometeoroids impact on the Hermean surface, the resulting local temperatures can reach roughly 5000 K. With such high temperatures and the resulting pressures, these impacts vaporize portions of the surface and can release even refractory elements into the exosphere [13].

Currently, research efforts into the constituents of Mercury's exosphere focus on neutral species, especially sodium which has been studied extensively in the literature {cf. [14], [15], [16]}, and positive ions [17]. The sole in-situ data of oxygen, from Mariner 10 as re-examined by Shemansky, suggests a near-ground density of 4.4×10^4 cm^{-3}. In this same paper, the sodium near-ground density is given as $1.7 – 3.8 \times 10^4$ cm^{-3}, as can also be seen in table 1 below [18].

If one includes even the weak intensity emission lines, the spectra for O I (i.e. neutral oxygen) extend from 685.544 to 26,173.56 Å, or from the ultraviolet to the infrared portion of the electromagnetic radiation spectrum. For positive ionization, the spectra are known to shift, so that for O IV (i.e. O^{3+}) the spectra are confined to the ultraviolet region from 195.86 to 3744.89 Å. Similarly, for O V (i.e. O^{4+}) the spectra covers the ultraviolet to visible range from 124.616 to 6500.24 Å [19]. Thus, the spectra for negative ions of oxygen would probably fall within the ultraviolet to infrared band regions as well.

Table 1: Revised g-values at Mercury [18]

Species	Wave-length (A)	$g(s^{-1})$	N^0 (cm^{-3})
H*	1216	5.3×10^{-3}	23,230
He†	584	5.1×10^{-5}	6×10^3
OI‡	1304	2.1×10^{-5}	4.4×10^4
Ar§	867	5.5×10^{-8}	$<6.6 \times 10^6$
N_α	5890, 5896	2.45, 1.22	$1.7\text{-}3.8 \times 10^4$
K	7664, 7699	3.24, 1.67	5×10^2

*$I = 2.25 \times 10^{11}$ Ph cm^{-2} s^{-1} at 1 AU; $I\nu/I = 1.42 \times 10^{-2}$ cm.
†$I = 1.28 \times 10^9$ Ph cm^{-2} s^{-1} at 1 AU; $I\nu/I = 3.52 \times 10^{-2}$ cm.
‡$I = 5.19 \times 10^9$ Ph cm^{-2} s^{-1} at 1 AU; $I(1,2)/I = 0.25$; $I(1,1)/I = 0.333$; $I(1,0)/I = 0.417$; $I\nu/I = 7.9 \times 10^{-2}$ cm.
§$I\nu = 5.86 \times 10^5$ Ph cm^{-2} s^{-1} $(cm^{-1})^{-1}$ at AU.

Note that the g-values in table 1 are specific to the case of zero velocity, and g-values are velocity dependent, as is discussed by Killen et al. [1].

Given that oxygen is expected to account for 60% (by weight) of the Hermean crust, one would expect it to be significantly more abundant than sodium [13]. McGrath et al. estimated the sodium abundance in Mercury's crust to be about 0.2% [20]. As a rough calculation, if one neglects the difference in mass between oxygen and sodium, and we increase the estimate of sodium abundance to 1%, oxygen should be about 60 times as abundant at Mercury than sodium, with a density of roughly 1.8×10^6 cm^{-3}, so why is all this oxygen not detected?

Since oxygen has an electronegativity of 3.44 on the Pauling scale [19], one possibility is that the oxygen that is released from the surface, whether it be through sputtering or impact vaporization, actually captures an electron from the Hermean regolith and is thus released as a negative ion. The electron component of the solar wind may also contribute slightly to the population of electrons available at or near Mercury's surface for capture by just-released oxygen atoms. With the current suite of instruments available on MESSENGER and the upcoming BepiColombo missions, the negatively charged constituents of Mercury's exosphere will not be measured, and thus we may miss out on fully understanding why oxygen does not appear to be the major constituent of the Hermean exosphere even though it is the most abundant constituent of the regolith [21].

Conclusion

Since the ions in the solar wind are positively charged, it is not too surprising that in the field of solar and space physics not too much emphasis has been placed on negative ions. The spectra and g-values of negative ions of the relatively light species often encountered in heliophysical research are not known at this point in time. Since the solar wind contains electrons as well as ions, it is plausible that in interactions with solar system bodies with tenuous atmospheres these electrons and others released at the surface by solar radiation may actually be captured by electronegative atoms or molecules, such as oxygen for example. In the case of Mercury, one must further take into consideration the interactions with the planet's intrinsic magnetic and electric fields, which can both guide where solar wind electrons and ions impinge on the surface, as well as alter the course of subsequently released regolith particles, be they positively or negatively charged.

We hereby recommend that funding be made available for determining the emission spectra of negatively charged ions, such as oxygen and other species commonly measured in space missions, as well as their corresponding g-values. Based on these spectral measurements, from laboratory and theoretical research, the heliophysics community can then begin work on creating spectrometers that are capable of measuring negatively charged ions. Subsequently, the g-values can be utilized to interpret the intensity measurements from this new generation of spectrometers as corresponding densities of the measured negative ions. The ability to utilize remote optical sensing techniques to measure negative ions, whether it be through ground-based observations or spacecraft-mounted instruments, could open up a new area of study in the field of solar and space physics. This new approach could help us to gain a better understanding of the mysteries of the innermost planet, Mercury, as well as the atmospheres of other planets and even comets. When one considers that the combined partial pressures of the detected species in Mercury's exosphere lead to a total that is roughly 2 orders of magnitude lower than the total exospheric pressure measured by Mariner 10 [22], determining the abundance of negatively charged ions in Mercury's exosphere could be an important step in finding all the constituents of the Hermean exosphere.

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WHITE PAPER : SOLAR AND HELIOSPHERE PHYSICS DECADAL SURVEY 2013-2022

EXPLORATION OF THE URANUS MAGNETOSPHERE

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1) Overview

Our understanding of the interaction between the sun and Earth's magnetosphere has been deepened by the exploration of the Jovian and Saturnian magnetospheres by the Galileo and Cassini spacecrafts. In the last decade we have discovered that the magnetospheres of Jupiter and Saturn are much more different from Earth's than previously thought, involving many processes which have no direct terrestrial analogs. In particular, the magnetospheres of these gas giants revealed themselves to be full of plasma, created through the volcanic activity of inner satellites (mostly Io and Enceladus). These internal plasma sources dictate a large part of the dynamics of the Jovian and Saturnian magnetospheres. The study of these different magnetosphere gave us a point of comparison for the study of the processes occurring in the Earth magnetosphere.

The better understanding of the Jupiter and Saturn magnetospheres these missions gave us also allowed the community to better define the unanswered questions and design spacecraft better adapted to answer them. Two such examples are the Juno mission, which will study auroral phenomena and the Jovian magnetic and gravitational fields from a polar orbit, and the EJSM mission, which will, in part, study the interactions between the magnetosphere and its satellites.

However, if we are to fully understand what it means to live with a star, we must gain a full understanding of how every magnetosphere in the solar system interacts with our star, including those magnetospheres in the outer solar system that exhibit extreme dynamics.

Despite the gains we have made understanding planetary magnetospheres and their interactions with the sun, there are still major gaps in our understanding of the magnetospheres of Uranus and Neptune. These systems are characteristically very different from the other magnetospheres in the solar system. These ice giants were briefly visited by Voyager 2, which showed planets and magnetospheres whose characteristics are very different from the terrestrial and gas giant systems. From a magnetospheric physics point of view, the Uranian system is the most fascinating as not only is Uranus's rotation axis nearly aligned with its orbital plane (i.e. tilt ~ 98°), but also its magnetic dipole axis is tilted ~59° from the rotation axis and very off-centered [Q3 magnetic model, Connerney, et al. 1987]. This atypical magnetic configuration introduces intriguing questions. We propose here a Middle size mission to explore the Uranus magnetosphere.

The next Flagship mission will explore the Jovian or the Saturnian system. Although Uranus and Neptune are not slated for a flagship mission, the Neptunian system would be a logical choice for a following Flagship mission, particularly due to the presence of cryovolcanism on its satellite Triton. Hence, no large mission to Uranus might be sent before a few decades. Nevertheless, Uranus is closer and presents a more intriguing magnetosphere, urging for an exploration mission. The smaller middle size mission we propose is designed to answer to the most compelling questions about the Uranus interior and magnetosphere, and can be launched in a shorter term.

This mission will provide data that can lead to a better understanding of the Uranus magnetosphere and how it interacts with the solar wind. As we show in the following, the Uranus magnetosphere is a perfect laboratory to test our knowledge of the magnetosphere interaction with the solar wind under unusual conditions.

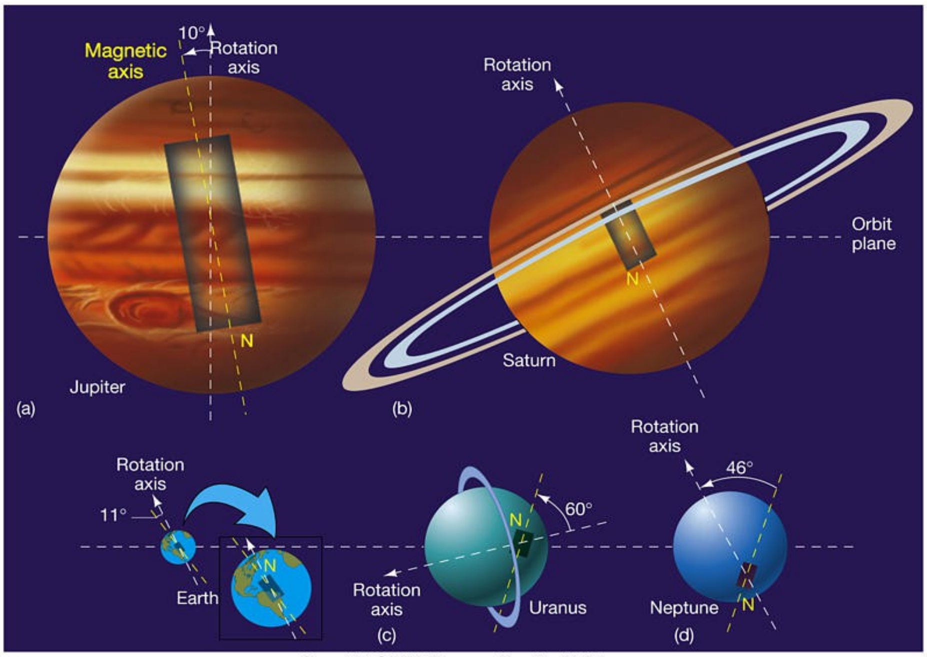

Figure1. *Sketch of the tilts of the rotational and magnetic axis of the magnetized planets of our solar system. The sketch shows Uranus rotational axis and dipole tilt at the solstice, in the configuration observed by Voyager 2.*

2) Scientific motivations

We expose hereafter a summary of the most compelling questions about the Uranus magnetosphere, and the way its study will benefit to our understanding of the magnetosphere physics in general. A more detailed description of the scientific motivations can be found in a companion white paper [Rymer et al., 2010]

How does the Uranus dynamo generates the planet's unusually tilted magnetic field? The most compelling scientific goals of a mission to Uranus are the mapping of Uranus's gravitational and magnetic fields, the latter being of the greatest importance for magnetosphere physics. Polar orbits are the most successful for obtaining this mapping, as they permit the measurement of the fields at all latitudes and longitudes, as well as passing through the auroral regions. However, such orbits are generally difficult and fuel consuming to achieve. Only Earth, Mars and soon Jupiter (with the Juno mission) have had polar orbiters. **The large inclination of Uranus is ideal for a polar orbiter as**

any trajectory confined to the ecliptic plane is a nearly polar one, allowing for a complete mapping of Uranus gravitational and magnetic fields.

<u>*How does the solar wind interact with a magnetic dipole oriented toward the sun?*</u> All of the magnetospheres explored up to now have magnetic dipole axes oriented almost perpendicularly to the ecliptic plane. Therefore, the nature of the interaction between the solar wind and a magnetic dipole oriented toward the sun is largely unknown. The exploration of such a system will open new horizons for magnetosphere physics. Due to the 59° tilt of the Uranian magnetic dipole, the magnetosphere will be in such a configuration about seven years before equinox, in 2042. In 2028, for the solstice, the dipole orientation will be almost constant at 59° from the sun direction, constituting the less exotic configuration. Still, this angle is smaller than at Earth (~67°), Jupiter (~80°) or Saturn (~90°). No spacecraft can reach Uranus before 2030, when the minimum angle between the sun direction and the dipole will be about 50° and decreasing. **This small angle presents an interesting laboratory in which to test theories of the interaction between a magnetosphere and the solar wind.**

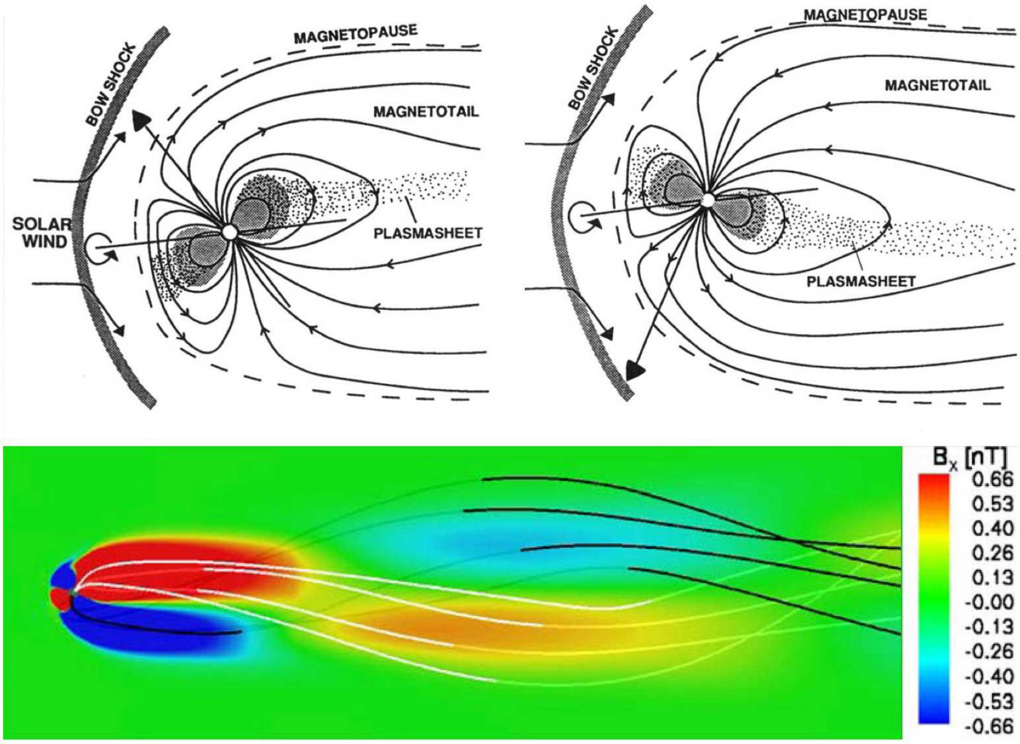

Figure 2. (upper panel) *Sketch of the magnetic field lines deformations due to the interactions of the magnetosphere with the interplanetary magnetic field and with the equatorial current sheet at Uranus, at the time of the Voyager 2 flyby (solstice).*
(Lower panel) Simulation of the magnetic field line toloplogy for a solstice configuration. The large angle between the magnetic and rotational axis lead to a twisted current sheet.
These sketches, adapted from Bagenal [2009], an simulation were realized from a single flyby, a the detail of the magnetic field topology and of the current sheet behavior are not precisely known.

<u>*How does the magnetosphere reacts when its configuration relative to the solar wind changes rapidly?*</u> The interaction between a magnetosphere and the solar wind depends strongly on the relative directions of their magnetic fields at the interface. The non-alignment of Uranus rotation and magnetic dipole axes leads to a complete change of the magnetic configuration in a few hours. When the rotation axis is oriented toward the sun, the magnetosphere and solar wind magnetic

fields change from parallel to anti-parallel in less than 8 hours. Since large-scale magnetic reconnection, which is the main driver of the Earth-solar wind interaction, occurs only for anti-parallel fields, this quickly changing magnetic field orientation at the magnetopause boundary must strongly affect the driving mechanisms of the Uranian magnetosphere (Figure 2). **This makes Uranus the perfect laboratory to test the models against a quickly and strongly varying environment.**

How are current sheets influenced by the tilt of the magnetic dipole relative to the planet's rotation axis and by the magnetosphere configuration relative to the solar wind flow? In the terrestrial magnetosphere, and even more in the gaseous giant magnetospheres, the equatorial current sheet strongly influences and drives magnetospheric dynamics. The equatorial current sheet consists of plasma confined in the centrifugal plane, which is located between the rotational and magnetic equatorial planes. The currents circulating through this plasma are responsible for a large part of the magnetosphere dynamics, and result in auroral phenomena. It is unclear where this current sheet exists in a system where the rotational and magnetic equatorial planes are almost orthogonal and, if a Uranian current sheet does exist, what role it plays in magnetospheric dynamics and in the auroral phenomena. **Understanding the Uranian current sheet is essential in determining the origin of the auroral emissions seen by Voyager 2 and from the ground** [Herbert, 1994]**.**

3) Observations to perform, Instrumentation required

Magnetosphere dynamics is a consequence of plasma-magnetic field interactions. The primary goal of the mission is thus to measure the characteristics of both the plasma and magnetic fields present in the Uranian system. This requires a complete mapping of the magnetic field, which is easier at Uranus than at any other planets as polar orbits are easily achieved. To perform these measurements the spacecraft will have to carry magnetometers similar to those on-board Juno. It also requires to measure the density, temperature, composition and flow direction and velocity of the magnetospheric plasma. A Langmuir probe permits to determine the plasma density, and ions and electrons spectrometers to determine the other parameters. For these instruments to perform best, a spinning spacecraft is preferred to allow for complete 3D coverage.

Finally, measurements of the electric currents and electromagnetic fields are essential for understanding the interactions. These can be performed by an electric field sensor and magnetic search coil for the local measurements, whereas magnetospheric currents and acceleration processes, characterized by electrons accelerated to energies ranging from a few keV to a few tens of keV, can be remotely characterized through the auroral emissions they generate.

A full set of auroral measurement instruments generally consists of a Low-Frequency Radio (LFR) receiver and both Infrared (IR) and Ultraviolet (UV) spectro-imagers. Each of these wavelengths gives different, complementary information about the auroral current system(s):

● UV observations are used to derive the power precipitated on the planet and the energy of the precipitating electrons. These two parameters characterize the auroral current systems by providing insight into the auroral acceleration processes.

● IR observations also permit one to obtain the power precipitated, as well as yielding information about the ionospheric response to the current system.

● LFR observations provide a large set of parameters, perhaps most importantly the rotation rate of the planet, which is a key parameter in nearly all physical aspects of a planetary system. LFR observations also provide the power precipitated, the energy of the electrons involved and eventually the nature of the auroral acceleration processes, and images the auroral emissions at different altitudes above the planet [Cecconi et al., 2009]. It can also detect the presence, or not, of lightnings in the atmosphere, which is important to understand the climate on Uranus.

Considering that the mass and power constraints for a Uranus mission may not allow for all remote sensing instruments, a radio receiver should have first priority.

In conclusion, a magnetosphere-oriented mission to Uranus must at least carry:

- Magnetometers to determine the magnetic field structure (similar to Juno's FGM+SHM instruments).
- A radio and plasma wave package, including direction finding capabilities, to accurately measure the planet rotation rate, provide auroral observations and measure currents (similar to CASSINI's RPWS package, or Juno's WAVES+direction finding).
- An ion mass spectrometer and an electron spectrometer to determine the plasma composition, density and temperature (Similar to Juno's JADE) and an energetic particle detector (similar to New Horizons' PEPPSI).
- Dual-frequency radio transmitters, which have almost no power or mass costs and provide important information about the planet interior. They also are part of the minimum recommendations of the Uranus mission white paper submitted to the planetary science decadal survey [Hofstadter, 2010].

Such a set of instruments answers the most compelling questions about Uranus's magnetosphere and about its interactions with the solar wind. Based on the experience of the previous New Frontiers missions, such a minimal payload can be optimized to run with less than 50 W of electrical power (not accounting for the radio transmitters).

In case of sufficient mass and power allocation, a payload similar to JUNO's would provide a set of instruments sufficient to answer most of the fundamental physics questions for a planetary magnetosphere, atmosphere and interior.

4) Mission feasibility

Mission opportunity: launch windows and mass limitation

A recent JPL study investigated the logistics of sending an orbiter to Uranus. This study showed that, in term of mass, a middle size mission carrying about 100 kg of science payload could be put on a polar orbit. This is sufficient for the minimum payload we propose, and therefore the mass of the spacecraft not the primary limitation to a Uranus mission. The best launch window is in 2018 for a chemical propulsion only scenario, as it allows for a Jupiter gravitational assistance. A much broader window is possible if electric propulsion is used. Flight times to Uranus orbit insertion are typically 8 to 12 years, meaning an orbit insertion in 2030 for a 2018 launch.

The JPL study envisioned a solar panel powered spacecraft, with solar panels producing 100 W at Uranus. This power is not sufficient, and therefore a larger surface area of solar panels is required at the cost of several hundreds of additional kilograms. However, if the solar panels were to be replaced by RTGs more mass could be allocated for the science payload, and a science payload equivalent to Juno's (a bit more than 170 kg) would be possible. Another possibility envisioned in the JPL study is an electric propulsion system, such as the one used for NASA's Deep Space 1 and Dawn missions. This option would greatly benefit to any solar-powered mission. As the spacecraft need a power of 100 to 200W to run at Uranus, a much larger power would be generated by the solar panels along the way to the planet, which could be used for the spacecraft propulsion.

Electrical power supply: Solar Panels versus Radioisotope Thermal Generator (RTG)

The biggest problem with a mission to Uranus comes from the electrical power supply. The New Horizons spacecraft – which has strict power limitations – needs 150 W to run, plus 30 W for the science payload. A spinning spacecraft requires a few tens of Watts less, since it does not require power-consuming attitude control components. Nevertheless, the New Horizons spacecraft electrical production expected at Pluto – a bit less than 200 W – may constitute a reasonable lower limit, given the minimal set of instruments we defined.

The solar constant at Uranus is ~3.7 W/m^2, implying that even the most efficient solar panels would not generate much more than 1 W/m^2. Therefore, even taking into account improvements in solar panel technology, a solar-powered spacecraft at Uranus needs much more than 100m^2 of solar panels, which has a high mass cost. Hence, an RTG-powered spacecraft is the best option, as it weighs much less and solves power supply difficulties, which allows for a larger science payload. However, new supplies of Plutonium 238 are necessary to build new RTGs. NASA funding has been approved, so that preliminary studies can be performed while waiting for the Department of Energy funding approval. Another possibility is a joint mission with the European Space Agency, which is planning to build Americium 241 based RTGs before then end of the decade. Nevertheless US-built RTGs are preferable, since ^{241}Am has a four times lower power-per-mass efficiency than ^{238}Pu.

Cost estimate

The JPL study showed that a middle size mission, launched by a Atlas 521 rocket, can be put into orbit around Uranus after a ten year travel, and the science payload is comparable to that of the previous New Frontiers mission, New Horizons and JUNO. Thus, this mission can fit in the New Frontiers cost constraints. The biggest issue, which could lead to higher costs, is the electric power supply. Depending on the availability of RPGs, or on the progress in solar panel technologies, the cost may be very different. An international collaboration would permit to share the cost of the development of new power supplies.

5) Summary

If we are to fully understand what it means to live with a star, we must gain a full understanding of how every magnetosphere in the solar system interacts with our star. After the exploration of the inner rocky planets, which revealed very different interactions with the solar wind, depending on the presence or not of a strong planetary magnetic field, and after the exploration of the giant gaseous planets, with the huge magnetospheres whose dynamics is dominated by the internal plasma sources, the next step of the solar system exploration is the study of the magnetospheres of the ice giants, Uranus and Neptune.

We propose here a middle size mission to Uranus. This mission will reveal many of the Uranus magnetospheres mysteries with a limited instrument package and a limited cost. It will also provide important information for a following mission to Neptune, which may be more suitable for a next Flagship mission, particularly because of its one-of-a-kind satellite Triton.

Hence, we propose a smaller Middle size orbiter to Uranus, with three main goals:

- Determine the planet's magnetic field and explore its exotic magnetosphere

- Test the models which have been developed for more steady magnetospheres, to improve our general understanding of the magnetosphere dynamics, and of the interaction of the magnetosphere with the solar wind under different conditions.

- Investigate the source of Uranus unusual magnetic field, by measuring the planet gravitational and magnetic fields and precise its rotation period.

Such a mission requires a small number of instruments, which are part of the basic payload of most spacecraft, and in particular of all of the New Frontiers missions. JPL's preliminary studies showed that such a mission could be done for a cost consistent with a middle size mission.

It will be the first orbiter sent to the only class of planets which have never had any, the ice giants. This first small mission would provide new knowledge about our solar system, about the magnetosphere physics and about the planetary science in general. This may have important consequences for the study of the Neptune-Mass extra-solar planets which are detected, thus improving our knowledge of how extra-solar planet live with their own stars.

Finally, being the first mission sent to the ice giants, it would provide very important constraints on the design of a following larger mission to Uranus or Neptune.

There are two possible options for the mission:

- A RTG-powered mission, with only tested technologies. This is the safest option, which also allows for the largest science payload. Nevertheless, new supplies of Plutonium 238 have to be found, or a collaboration with ESA has to be set to obtain RTGs.

- A technology development mission, powered by large solar panels, which have to be developed, and propelled by plasma thrusters. This is more risky, and may be more costly. Moreover, due to the larger weight of the solar panels, and the reduced power available, this option does not allow for a large science payload. Nevertheless, as more missions to the outer solar system will be planned, such a mission would help to develop new technologies which may reveal themselves less expensive over time.

In both cases, international collaborations would be beneficial to reduce the costs and solve technological difficulties.

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The Future of Modeling the Space Environment

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Summary

Our ability to simulate the space environment is an increasingly important capability that helps us place observations in context, explore the implications of new theoretical ideas, and make predictions. Computational models that simulate the space environment have significantly increased both their capabilities and complexity over the past decade. Gone are the days when a single investigator could develop a state of the art model and use it to make important scientific advances. Instead a cohesive team of space and computational scientists, along with software engineers, is needed to develop, validate, maintain, and exploit a space environment simulation model. Funding agencies need to understand this development, and create funding models that support such modeling teams.

The importance of space environment models

As space environment models continue to become more sophisticated, making full use of increased computation power to increase spatial and temporal resolution, include more physics, and expand the size of the region they simulate, they have become more accurate and hence more useful as both scientific and operational tools. Computational models are used to simulate all regions covered by this decadal survey, from the solar interior and magnetic dynamo, through the solar atmosphere and corona, to interplanetary space, the heliosphere and its interaction with the local interstellar medium, and the upper atmospheres, ionospheres and magnetospheres of the planets and other solar system bodies. Indeed the coupling between these various regions has become an increasingly important part of our discipline and hence of our modeling efforts.

Models that simulate the space environment are important for a number of distinct uses. Here I outline three such uses.

Interpreting Observations: The limitations on making observations of the space environment, for example the difficulties of obtaining broad simultaneous spatial coverage of the magnetosphere or solar wind, or the difficulties of obtaining in-situ observations of the corona, or any direct observations of the solar dynamo, make the interpretation of the observations that we do have particularly challenging. Models play a critical role here. By modeling the region being observed, the observer can test various interpretations, see how the observations might play into the broader spatial context, or how the local physical processes might produce the indirectly or remotely made observations. Since the observational researchers are not usually themselves also modelers, this use places a further constraint on model developers, as they must produce well documented, validated, robust and relatively easy to use versions of their models that can be used by scientists who are not expert in their use.

Numerical Experiments: Models provide our only way to experiment with the systems we study. Our observations are limited by what nature provides and by the incomplete set of quantities that we are able to measure. Large geomagnetic storms are (fortunately) rare. The solar wind and interplanetary field is never steady. Solar magnetic fields are never simple. With observations it's often difficult or impossible to separate the effects of competing physical processes (e.g. wave heating and magnetic reconnection). With models it is relatively easy to perform numerical experiments to explore the relative contributions of competing processes, or to see how a system responds to particular inputs. Thus models provide the means to really explore the physical processes that control the space environment.

Operational Predictions and Forecasts: As we continue to develop technological use of space, and our ground-based technologies continue to become more sophisticated, we become ever-more vulnerable to the effects of space weather, and rely more heavily on space weather specifications and forecasts. The role of computational simulation models as operational specification and forecast tools is rapidly evolving. NOAA is in the process of installing the first large-scale numerical space weather model (WSA-Enlil) on the National Center for Environmental Prediction (NCEP) operational computers to be operational in 2011. As simulation models improve and as the space weather forecasters become more confident in using them, the use of space weather models as operational tools will only increase.

The evolution of space environment modeling.

The first truly global space simulation models were developed during the 1980's to run on the first generation of super computers. During the 1990's these models established themselves as useful tools for the study of solar and space physics, particularly through the support of the ISTP program. During the past decade, as our understanding of the complex coupling processes active in space has improved, space environment models have been further developed. Making use of increased computational capabilities, the models have increased in size and complexity, running on increasingly-large grids with improved resolution, and using more sophisticated solution schemes to run more efficiently. Not only have the models themselves increased in sophistication and complexity, but they are increasingly run coupled to other models in order to add more physics, for example to model geospace, thermosphere, ionosphere, radiation belt, and ring current models have been coupled with global MHD magnetosphere models to produce more realistic comprehensive models.

Whereas the first generation of models were usually built by a single investigator or a very small group of collaborators, and often could only be run by them, modern models require a team of experts to develop, maintain and validate them, and make the models accessible to the scientific community. At the very least, the team should consist of space scientists who understand the physics being simulated, computational scientists who understand numerical techniques and efficient algorithms, and software engineers who can build and implement the codes to run on evolving computing platforms. In addition, sophisticated visualization and analysis software is required to access and analyze the vast amount of data the models generate.

The need to provide appropriate support for space environment modeling teams

Throughout the past decade space environment modeling has received substantial financial support from the various funding agencies. The Department of Defense has supported several Multidisciplinary University Research Initiative (MURI) modeling projects, NASA has supported modeling through its Living With a Star (LWS) Strategic Capabilities program, and NSF through a Science and Technology Center (STC). These sustained collaborative funding sources have allowed space environment models to develop to their current sophisticated state through funding coordinated teams of scientists and software engineers. These teams have produced an amazing variety of complex models that between them (and in various combinations) can model the space environment from below the solar surface to the heliopause and the mesopause.

However, we are far from done. To maintain these models and to continue to improve them, build new ones to meet both scientific and operational forecast needs and train the next generation of scientists requires the continued support of teams such as those that have brought us to our current state of affairs. Just as building a sophisticated space instrument or a spacecraft requires a dedicated team with a broad range of expertise, and the security to be able to devote themselves to the project, so does development of a model. It requires funding that is sustained and at a level to support a cohesive team. For the past decade through a fortunate series of events or circumstances, such funding was provided. To maintain what we now have and move us forward in our modeling capabilities, the funding agencies, either individually or collectively, should continue to provide this level of support. In order to provide the breadth and depth of expertise and the stability needed to undertake major projects, this support needs to be sufficient to maintain teams of at least 4 or 5 FTE's for a period of 5 years or so. This will be a significant commitment by the funding agencies, but it is crucial in order to maintain and exploit the scientific community's modeling capabilities and expertise.

A Science White Paper in response to the 2013-2022 Heliophysics Decadal Survey

Fundamental heliophysics processes

Unsteady wandering magnetic field lines, turbulence, magnetic reconnection, and flux ropes

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1. abstract

Magnetic flux tubes or flux ropes are the building blocks of magnetohydrodynamics (MHD). The interactions of flux ropes are key to understanding the unsteady dynamics of energy conversion, both magnetic to kinetic (reconnection) and kinetic to magnetic (dynamo). In nature, much of the basic MHD physics of reconnection, turbulence, dynamo, and magnetic topology evolution is irreducibly three dimensional (3D). Very little is known about the ramifications of this fact. We argue that much can be learned from *experimental* work in MHD relevant 3D systems. It is possible to scale dimensionless parameters to distill the essential physics, and for example assist data interpretation from existing and future spacecraft, as well as unravel the fundamental processes. There exist two linear (i.e. not toroidal) experimental devices, with fully 3D freedoms to evolve the plasma physics, that can tackle this problem: the Reconnection Scaling Experiment (RSX) at Los Alamos and BaPSF at Univ. California – Los Angeles.

2. Science objective

Explore fundamental 3D interactions of the flux rope building blocks of MHD

3. Introduction

3.1. Magnetic structure in 3D

Magnetic field is a unifying feature of heliophysics. These field lines occupy cross sectional areas, and fill up three dimensional (3D) volumes as flux tubes, and obey Newtonian mechanics and magneto-hydro-dynamics (MHD) equations of motion. If there is a vector component of the current parallel to the magnetic field, then the flux tube is a twisted flux rope. The rope geometry can be ubiquitous even in laminar sheets, since multiple reconnections in the inherently unstable current sheet create flux ropes (magnetic islands in 2D), and are often observed on the sun and the rest of the heliosphere. There are four 3D, topologically possible, classes of flux tube interactions [Linton2001]: (1) bounce (no appreciable reconnection), (2) merge, (3) slingshot (the most efficient reconnection), and (4) tunnel (a double reconnection).

Understanding the unsteady dynamics of flux ropes and their mutual interactions offers the key to many important solar phenomena including magnetic reconnection and turbulence, which cross the traditional heliophysics subdomains of the Sun, heliosphere, and magnetosphere. Observations [Frazier1972] show that the magnetic field of the Sun occurs in flux-tube bundles in the solar atmosphere, so flare models commonly invoke flux-tube collision as the trigger for flares. Tangled, unsteady magnetic field lines and flux ropes are ubiquitous, for example on the sun from differential solar rotation, in the corona, solar wind [Borovsky2010], and the magnetotail. 3D isolated X-lines, kink dynamics and bursty driven dissipative reconnection processes may be related to reconnecting bursty bulk flows in the plasma sheet, solar corona and magnetotail turbulence. Astrophysical turbulence and 3D statistical mechanics of wandering flux ropes [Lazarian1999] are likely related.

3.2. Reconnection in 3D

For more than half a century it has been realized that processes associated with magnetic reconnection [Biskamp2000] are key to global changes magnetic topology in astrophysical [Kulsrud2005], solar [Priest2000], magnetosphere [Mozer2003] and laboratory [Yamada1999] plasma environments. Energy stored in stressed magnetic fields can produce large scale explosive events, that spontaneously evolve due to unsteady and impulsive [Bhattacharjee2004] local dissipative processes to energize particles. Explanations of satellite observed fast reconnection rates require patchy [Galeev1986] [Yin2008] yet volume filling processes, that can only exist in three dimensions (3D) [Titov1999]. At a fundamental level, reconnection generated current sheets are inherently prone to 3D instabilities, which creates a hierarchy of successively smaller spatial scales, that are generally not accounted for with 2D theory or simulations.

3.3. Questions cf reconnection in the heliosphere-magnetosphere

Does magnetic topology have a crucial role, and how does it affect the physics of reconnection? 2D models have been important to guide our physical picture of magnetic reconnection. On the other hand extension of these concepts to 3D is far from straightforward. Indeed, 3D magnetic field structure can be quite complex.

- How does 3D reconnection work: unsteady onset, evolution, and termination?

- How, when, and where is reconnection initiated?
- Can we identify typical situations for the onset of reconnection? Non driven examples?
- Is there a usually a dominant mechanism such as increased current density, decreased magnetic field, or increased magnetic shear, 3D localized resisitivity?
- How does reconnection terminate?
- Does back reaction of piled up magnetic and kinetic pressure stagnate the processes?
- Can we quantify the role of flow fields?
- Is there a topologically plausible continuum of possibilities spanning anti-parallel reconnection as observed at low latitudes in the presence of northward Interplanetary Magnetic Field (IMF) to component reconnection as observed at higher latitudes with southward IMF?

4. Value to satellite missions

4.1. Multi spacecraft data

Unraveling these major unresolved heliosphere and magnetosphere reconnection physics puzzles is a primary scientific goal of the 4 spacecraft Magnetospheric Multiscale (MMS) mission [MMS2009], a Solar-Terrestrial Probe. MMS has been designed with diagnostic capabilities to investigate transient, unsteady and 3D magnetic, electrostatic, and flow structures. At any given time, four data points in space are collected. This is sufficient to infer many features, but important spatial derivative-like quantities such as curl, divergence, vortices, or simultaneous small and large scale correlations are difficult to evaluate unambiguously. Distinguishing between temporal and spatial variations has been made possible with coarse grained resolution with clusters of similarly instrumented spacecraft such as CLUSTER and THEMIS, and soon MMS. However in the laboratory this distinction can be measured with high accuracy in both time and space.

What types of 3D magnetic structures will the MMS mission likely observe? A 3D magnetic null configuration has been statistically inferred from CLUSTER data [Xiao2006], but the evidence is not detailed in 3D, and is far from solid. What happens when there is a guide field, e.g. in many typical cases including smaller spatial scales and turbulence, and a null cannot exist? What would the spacecraft see when there are stagnation flows, compressible effects, or local gradients? Collaborating spacecraft observational scientists will facilitate our interpretation of laboratory experiments, which in concert with magnetosphere data and simulations will provide our *only opportunity to nail down the answers* to these questions, and will increase the credibility of MMS (and other) data interpretation.

4.2. Reconcile spacecraft observations to experiment & simulation

By matching or scaling dimensionless parameters, with appropriate initial and boundary conditions, some natural phenomena can be studied on laboratory scales. Table 1 shows considerable laboratory overlap with MMS capabilities:

Diagnostic & Observation	**MMS comment**	**RSX resolution**	**RSX**	**VPIC resolution**
Electric field	yes	$< c/\omega_{pe}$	Triple probe, E=-dA/dt	$\approx \lambda_{De}$
Magnetic field	Yes	$< c/\omega_{pe}$	Magnetic probes	$\approx \lambda_{De}$
ion distributions	excellent	$< 4c/\omega_{pe}$	Energy analyzer	$\approx \lambda_{De}$
Ion speed	excellent	$< 4c/\omega_{pe}$	Tomography of chord averaged doppler shift H-beta	$\approx \lambda_{De}$
Ion temperature	excellent	$< 4c/\omega_{pe}$	Tomography of chord averaged thermal width H-beta	$\approx \lambda_{De}$
Electron currents	yes		J-env_{ion}	$\approx \lambda_{De}$
Wave disturbances	E, B, n	E, B, n $< c/\omega_{pe}$, $>\omega_{ce}$	Experimental probes, hodograms, data acquisition & bandwidth can be fast or slow, conditional sampling	$\approx \lambda_{De}$
Global angular momentum	Not obvious	$< c/\omega_{pi}$	magnetics, fast camera images, flows	Yes
Global 3D structure:	Not obvious	$< c/\omega_{pi}$	magnetics, fast camera images	yes
Number of spatially distinct data pts	4	$< c/\omega_{pe}$	2-10x10^3	grid cells > 10^9
Anti-parallel vs component reconnection	Depends on spacecaft location		adjustable	adjustable

Table 1. Survey of plasma characteristics accessible via spacecraft measurements, with their analogues in the RSX experiment and VPIC simulations. Sme features are tough to measure in space, but accessible in the laboratory and simulations.

We assume approximate magnetospheric environment parameters of B≈10 Gammas = 10^{-4} Gauss, density n≈$1cm^{-3}$, ion mass ≈ 1amu, where MMS cluster satellite separation is designed to be 10km or greater. The important scale lengths that must be considered include the Debye length which can be in the range λ_{De} ≈ 100m (possibly boom extension length of a single spacecraft), electron skin depth c/ω_{pe} ≈ 500km (resolvable with multiple spacecraft), electron gyroradius r_{Ge} ≈ 2-10km (possibly resolvable with multiple spacecraft). MMS burst time resolution can be better than 1msec, which corresponds to better than the electron cyclotron frequency f_{ce} ≈ 300Hz. Time resolution is better in the laboratory, even in dimensionless units.

5. Usefulness of experiment – theory – computational collaborations

5.1. Sparse experimental work on 3D flux rope dynamics, reconnection, turbulence

To our knowledge there is little or no laboratory work on possible links between reconnection and turbulence, and very little on the dynamics of intermittent, unsteady reconnection.

Many relevant helio, astro, and space plasmas are in the MHD regime, and therefore "frozen in" magnetic field lines serve as a proxy for flow. Magnetic field line locations and movements are much easier to measure in 3D in the laboratory than flow, and one can take advantage of experimental magnetic measurements to study magnetic field line, using flux ropes as proxies … to unravel macro and micro flow patterns and compare these with computational simulations. 3D magnetic field data allows us to find the B field line paths, and also to integrate along field lines global invariants such as entropy. The obvious exception is during magnetic reconnection inside the small diffusion region, where field lines lose their identity. A straightforward method to experimentally in RSX [Intrator2009] and LAPD [Lawrence2009] quantify these 3D quasi separatrix layers [Milano1999] is to measure magnetic field lines up to the boundaries of the diffusion region, and then calculate the slip-squash characteristics [Titov2009].

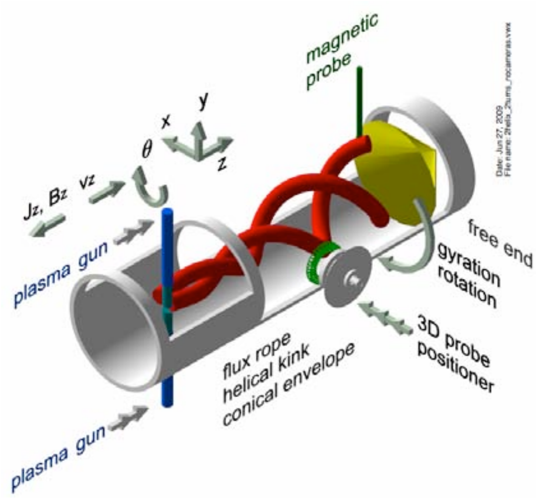

Fig. 1 RSX experiment schematic (2m long x 40cm radius), showing coordinate system, geometry, background axial magnetic field B_z (single arrows). Two plasma guns (double arrows) insert radially but create axial flux rope currents and net helical magnetic field. Two kinking flux ropes terminate at the external conical anode (triple arrow) which allows adjustable axial boundary conditions. Magnetic probes are inserted through 3D probe positioners. Radial excursion from the reference fiducial **z** axis exaggerated for clarity.

The RSX (Fig. 1) experiment has yielded 3D data that show the onset, stagnation, and cessation of magnetic reconnection [Sun2010] [Intrator2009] and also unexpected behavior of flux ropes [Furno2006] [Sun2008] [Sun2010]. The LAPD facility has demonstrated that 2D concepts such as the reconnection current sheet are better explained by 3D signatures such as the quasi separatrix layer [Lawrence2009]. This requires large 3D data sets, which complement spacecraft data with limited numbers of spatially separated data points for each time step.

6. Experiments + simulations connect micro to macro physics

Computational models must couple kinetic micro-physics of particles, waves and momentum transfer to macroscopic characteristics. Our collaborating magnetosphere observers and theorists can advise on reconciling laboratory and spacecraft data. By matching or scaling dimensionless parameters, computer codes can bridge the gap between nature and laboratory, while enabling benchmarks plus verification & validation for code predictions.

6.1. Experimental and computational resources

LANL has world class and unique capabilities for investigating 3D reconnection that is spontaneous or self driven by instabilities, using VPIC, a particle in cell code running at LANL on Roadrunner, using unprecedentedly large numbers of grid points, particles, and petaflop speed. The kinetic micro-physics of particles, waves and momentum transfer to macroscopic characteristics can be coupled via fluid simulations with the bulk properties. Also G. Lapenta has modeled RSX at Katholieke Universiteit, Belgium, using 3D particle code CELESTE-3D and variants and 3D fluid codes that he refined while at LANL. Massage and 3D imaging of huge 3D datasets has been carried out with LAPD data.

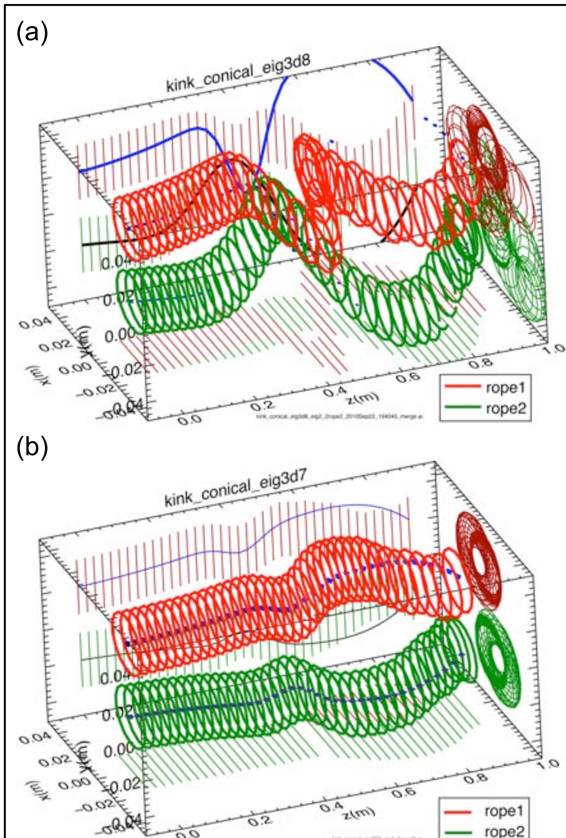

Fig. 2. RSX 3D magnetic data with model reconstruction. Flux rope building blocks of MHD dynamics include a variety of topologies, statistical mechanics, and final states not usually accounted for in the usual MHD picture. For example (a) Kinked flux ropes gyrate, parallel currents attract which yields expected merging/reconnection [Intrator2009]. (b) B_z field line bending forces restrain merging and flux ropes bounce! [Sun2010].

The unique Reconnection Scaling Experiment (RSX) [Furno2003] at Los Alamos National Laboratory showed for the first time [Intrator 2009] a plasma instability that initiated reconnection, with subsequent saturation or stagnation related to the fluid-like forces, mass, flows, and dynamics of the participating plasma and its current system. The electron diffusion region was experimentally resolved to electron skin depth scales. The Basic Plasma Science Facility performs frontier-level research on fundamental properties of the plasma state of matter. Usage of the facility is available to qualified scientists from national and international institutions, and industry.

7. Experiment descriptions

7.1. RSX

The RSX (wsx.lanl.gov) schematic in Fig. 1 includes a view of two plasma guns located at z=0 which are radially inserted into the center of the RSX cylindrical vacuum vessel. This forms two cylindrical plasma columns in the externally imposed constant, uniform, axial magnetic field of $B_{z0} \approx$ 10-1000 Gauss. A screw pinch is formed by driving a current in the plasma to an external anode [Furno2003]. When two flux ropes are created, their parallel currents (I_p mostly in the z direction) attract each other. The plasma is generated by plasma gun arc discharge, independent of initial conditions or evolution, without recourse to any complicated startup scenario typical of tokamaks, spheromak like coaxial guns [Bellan2000], or flux cores [Yamada1997]. This allows a wide independently adjustable range [Furno2003] for density, current density (skin depth), embedded magnetic field (gyro orbit size), and electron temperature (collisionality).

A special vacuum vessel section containing six 3D probe positioners allows many independent insertable probes to explore a 3D volume (dx•dy•dz = 15cm•10cm•30cm) with spatial relative accuracy better than 0.5mm in an x-y-z Cartesian coordinate system [Intrator2008]. This allows experimental resolvution to spatial scales where reconnection breaks MHD assumptions, i.e. electron skin depth which is typically 1-2mm in size. Fig. 2 shows two examples of theoretical reconstructions constrained by experimental data that show (a) merging and reconnecting flux ropes and (b) unexpected bouncing flux ropes. Probe data was built up over many repeatable shots, where we measured plasma density, electron temperature, and electron pressure on sub mm spatial scales.

7.2. BaPSF-LAPD

The Basic Plasma Science Facility (http://plasma.physics.ucla.edu) performs frontier-level research of the plasma state of matter. Usage of the facility is available to qualified scientists from national and international institutions, and industry. Research on the fundamental properties of plasmas aids our understanding of applications ranging from fusion energy to space science. It is a user facility operated at the University of California, Los Angeles. The core of the facility is a modern, large plasma device (the LAPD, Fig. 3) constructed by Walter Gekelman (the facility director) and his staff of research scientists and technicians. The publication profile is impressive (6 PRLs so far in 2010). The facility provides an environment in which teams with complementary expertise (e.g., Laser Induced Fluorescence or High Power RF) can come together to attack problems that they would not pursue individually. The operational procedures foster the exchange of technical information across diverse areas of research (e.g., fusion studies, space investigations, laser-plasma interactions, plasma applications) in which the basic properties of plasmas play an essential role.

Fig. 3. LAPD experimental device at UCLA

The facility is available to scientists from all institutions, national and international, with access to state-of-the-art hardware and a broad range of plasma conditions in which to exert their creativity. Through cooperative research programs involving researchers from large and small institutions, the BaPSF aims to yield major advances on outstanding problems related to the behavior of plasmas, and contribute significantly to the training of the next generation of plasma researchers. A much larger facility (ET, Enormous Toroidal experiment) is also being explored.

8. Relevance to the Decadal survey and Estimated cost

There is no steward organization for earth based *experimental* basic plasma physics capability, which is almost extinct in the present NASA program, and is primarily supported by NSF and DOE. Both experimental efforts (RSX, BaPSF) have large and vibrant student programs.

Multi point measurements in space and time, indeed massive 3D data sets, complement the spacecraft multi point (e.g. 4 spatial points per time step) capabilities. We make the case that a small investment represents a logical next step for Helio and magnetosphere physics, with huge bang for the buck. Our objectives extend across several of the National Capabilities Working Groups; namely, ‘Research to Operations’, ‘Theory & Modeling’, ‘Explorers’, and ‘Innovations’. The mission combines both operational and research objectives and therefore has both societal benefits and advances the state of knowledge for the Sun-Earth system.

The cost for fielding experimental work on earth is far less than a spacecraft mission, but more than an observer post doc with a computer. Expenses are typically post doc, student FTE, 15-20% allowance for materials and supplies, small fraction of PI and technician FTE, and some travel and publication expenses. Significant progress can be made for less than $300-500k/year per experiment.

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Next Generation Experiments for Laboratory Investigations of Magnetic Reconnection Relevant to Heliophysics

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Abstract

This concept paper describes the scientific opportunity for next generation laboratory experiments to study magnetic reconnection in regimes directly relevant to space and solar plasmas. In parallel to theory and simulations, dedicated laboratory experiments have contributed significantly to the understanding of fast reconnection in the past decade, such as validation of two-fluid effects and detection of microturbulence in the reconnecting current sheet. However, further critical contributions to space and solar plasmas in the coming decade are limited by the achievable values of controlling parameters in these ongoing experiments. The new theme of magnetic reconnection with multiple X-lines can possibly provide solutions for fast reconnection in large systems and for efficient particle acceleration as suggested by recent numerical and theoretical studies. To meet these challenges, new ideas for next generation experiments are emerging to provide the required experimental capabilities to study detailed reconnection process, efficient particle acceleration and spontaneous global self-organization in the parameter regimes directly relevant to space and solar plasmas.

1. Introduction

Magnetic reconnection, the efficient release of magnetic energy by topological rearrangement of field lines, is one of the most important and fundamental plasma processes in heliophysics. It plays key roles in a wide range of heliospheric phenomena from solar flares, coronal mass ejections, solar wind propagation and dissipation, interaction of interplanetary plasma with Earth and other planets' magnetosphere, dynamical response of planetary magnetopheres to solar wind such as magnetic substorms, and interaction of interstellar media with the heliosphere. Magnetic reconnection is considered to be a necessary part of dynamo processes in generating and maintaining magnetic field in the sun and in planetary cores. The importance of magnetic reconnection has been also recognized in more distant astrophysical plasmas, such as star formation and explosive phenomena from strongly magnetized neutron stars. Back on Earth, laboratory fusion plasmas often suffer from uncontrolled reconnection events that can adversely affect confinement. Therefore, understanding physics of magnetic reconnection is not only of fundamental importance for heliophysics but also with broader impacts across other disciplines.

2. Roles of Dedicated Laboratory Experiments in Understanding Reconnection

Despite the long history of magnetic reconnection research, the most important progress has been achieved only recently, especially during the past decade (see recent reviews [1,2]). Many parts of this progress were accomplished with contributions from dedicated laboratory experiments, which have become increasingly well-controlled and well-diagnosed. Below we list a few examples of these accomplishments.

- Quantitative tests of Sweet-Parker model [3]. This classical reconnection model proposed in 1950s was not tested experimentally until late 1990s. Significant modifications were required for quantitative agreements with experiment.
- Two-fluid effects for fast reconnection [4,5]. Existence of a quadrupolar out-of-plane magnetic field was predicted numerically [6], consistent with space data [e.g., 7], but definite confirmation by 2D measurements was done in the laboratory with theoretically predicted dependence on collisionality.
- Detection of electron diffusion region [8,9]. Its thickness was measured accurately and compared directly with state-of-the-art 2D PIC simulations. The comparisons challenged modeling and provided physical insights that 3D physics might be important in explaining the remaining disagreements with data. Detecting and studying the electron diffusion region is a goal of the MMS mission.
- Microturbulence in current sheets [10-12]. Predicted theoretically, electrostatic fluctuations were detected for lower-hybrid drift waves or electron phase space holes, but electromagnetic fluctuations were surprises to theory [13].
- Potential well and electron kinetics [14]. With measurements and physics understanding of electrostatic potential around the X-line, one can quantitatively explain the measured electron distribution function near the Earth's magnetotail.
- Ion heating by reconnection [15,16]. It was found in the laboratory that increments of ion energy are proportional to square root of ion mass or ion temperature is proportional to the charge-to-mass ratio. These findings may help solve the ion heating problem in the solar wind.
- Flux rope dynamics [17-21]. In attempts to be relevant to the dynamics of coronal loops, several experiments were performed either in linear or curved geometries with line-tied boundary conditions. Equilibrium and stability of the line-tied current loops is being studied quantitatively and compared with theories [e.g., 22].

It is clear from these examples that well-controlled and well-diagnosed experiments play increasingly important roles in understanding reconnection phenomena in heliophysical plasmas.

3. Outstanding Issues for Magnetic Reconnection in Heliophysical Plasmas

Despite significant progress in reconnection research, there exist a number of outstanding issues to be addressed before a better understanding of reconnection phenomena in heliophysical plasmas can be achieved.

- How is the reconnection rate determined? *(The rate problem)* Although two-fluid effects (e.g. the Hall term) have been shown to facilitate fast reconnection, the required efficient dissipation within the electron diffusion region is still elusive, and micro-turbulence in the current sheet can contribute to the solution of this problem. How does magnetic reconnection take place in partially ionized plasmas, such as in solar chromospheres where neutral particles dominate? Recent observations by HINODE show that reconnection-like energetic activity is abundant in these partially ionized plasmas.

- How does reconnection take place in 3D? *(The 3D problem)* In addition to the 3D microturbulence within the reconnecting current sheets, there are situations where the magnetic field vanishes in isolated three-dimensional points, or so-called 3D null points. Magnetic reconnection around these 3D null points or null-null lines [23] is important for understanding complex dynamics of the general magnetic topology, such as flux transfer events in the Earth's magnetosphere [24].
- How does reconnection start? *(The onset problem)* Large-scale reconnection phenomena, such as solar flares, coronal mass ejections, or magnetic substorms, often manifest themselves as impulsive relaxation events. Laboratory experiments [25, 26] and some numerical models [e.g. 27, 28] also exhibit spontaneous reconnection. However, it is unclear under what conditions these spontaneous reconnection takes place or whether these conditions are universal.
- How are particles energized? *(The energy problem)* Reconnection mainly manifests itself as an energetic process of releasing magnetic energy to plasma particles, sometime in the form of a high-energy tail of distribution functions [29-31]. Understanding how this process occurs is a major challenge. In addition to the acceleration due to single X-line reconnection, interactive multiple X-lines reconnection may provide a solution to this problem [32,33]. Additional possibilities, such as shock-based reconnection models, may be important to generate energetic particles [34].
- How do boundary conditions affect the reconnection process? *(The boundary problem)* It is not self-evident that reconnection physics in periodic systems can be straightforwardly applied to space and solar plasmas which are always non-periodic, and often line-tied at their ends [35]. Determining effects of boundary conditions is important to understand reconnection in heliophysical plasmas.
- How to apply local reconnection physics to a large system? *(The scaling problem)* Even all above issues are completely understood, there still exists an important issue on how to translate physics in small systems to larger heliophysical systems. When the plasma size

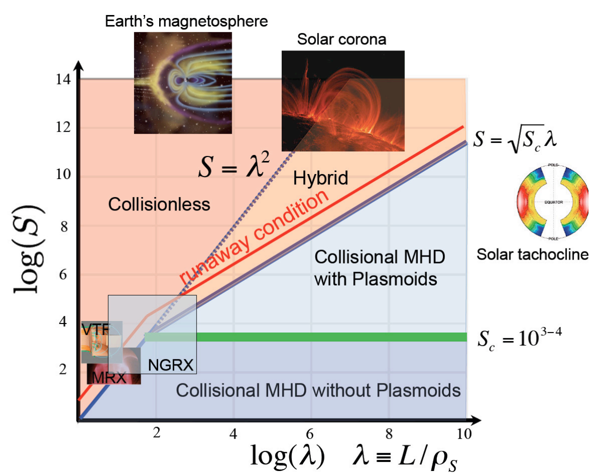

Figure 1. *A phase diagram for magnetic reconnection in 2D. If either S or the normalized size, λ, is small, reconnection takes place in collisional MHD (without plasmoids) regime or in collisionless regime. When both S and λ are sufficiently large, two new regimes appear: a regime for collisional MHD with plasmoids and a regime for collisional MHD plasmoids with kinetic current sheets in between. The regimes for reconnection in Earth's magnetosphere, solar corona, and solar tachocline are also shown. The existing experiments, such as MRX and VTF, do not have accesses to these new regimes while the next generation reconnection experiments (NGRX) should provide access to these relevant regimes for heliophysical plasmas.*

normalized by ion sound gyroradius, λ, and the Lundquist number, S, are sufficiently large, the reconnection physics derivates significantly from that either in small S or in small λ. A new phase diagram [36,37,28] emerged from recent large-scale numerical simulations [e.g., 38,39] as shown in Fig.1 where four reconnection phases are illustrated: collisional MHD without plasmoids, collisional MHD with plasmoids (corresponding to reconnection in solar tachocline), collisional MHD plasmoids with kinetic current sheets in between (or hybrid, corresponding to solar corona) and collisionless (corresponding to Earth's magnetosphere). In order to be directly relevant to reconnection phenomena observed in heliophysical plasmas, it is crucial for laboratory experiments to access all of these reconnection regimes. We note that reconnection in these new regimes is associated with multiple X-lines, and thus can possibly provide solutions to the onset problem and the energy problem mentioned above.

4. Existing laboratory experiments and their capabilities

Table I summarizes the capabilities by existing experiments for each issue listed above. With diversity in geometries and focus areas, these experiments are expected to continue to help address many of these outstanding issues into the next decades. Advancing in plasma diagnostics and interacting closely with observations, theory and modeling will continue to be a key. However, the critical issue of applying local reconnection physics leaned from these experiments to a large system, such as solar coronal plasmas, is difficult to be addressed due to the limited size and Lundquist number available in these experiments.

Issue	Existing Experiments	Opportunities for new Experimental Study
Rate	TS-3/4, MRX	Partially ionized plasma
3D	LAPD, MRX, SSX, VTF, Caltech	3D-null point
Onset	VTF	Global self-organization
Energy	3D-CS, LAPD, TS-3/4, MRX, SSX	Particle acceleration
Boundary	RSX, RWM, MRX, LAPD, Caltech	Non-periodic
Scaling	MRX	Large parameter space

Table I. *Outstanding reconnection issues addressed by the existing experiments and opportunities for new experimental studies.*

5. Opportunities and new ideas for next-generation reconnection experiments

Also listed in Table I are opportunities for new experimental studies in the coming decades for each outstanding issue. Among these, a major opportunity identified is to access the new reconnection regimes described in Sec. 3. Next generation experiments would therefore seek to achieve plasmas of normalized size on the order of 10^3 and Lundquist number on the order of 10^5 (see Fig.1). The physics of reconnection in these new regimes has more direct relevance with heliophysical plasmas than those already accessible by the existing experiments. With the capabilities to access these new regimes with multiple X-lines reconnection, the critical issues on particle acceleration, global impulsive relaxation, and non-periodic boundary conditions in a large system can be studied. Reconnection in partially ionized plasmas would be facilitated through larger plasma volumes. Shock-based reconnection models could also be tested more conclusively in larger plasmas.

New ideas for next generation experiments are emerging to meet these challenges. One example concept for such a next generation experiment is based on the Magnetic Reconnection Experiment (MRX) [40]. The MRX is a small experimental device dedicated for laboratory study of magnetic reconnection, using a set of specially designed internal coil assembles. Many significant results [3,4, 8,9,10,12,21,41,42] have been documented on a wide range of reconnection processes from collisionless to collisional, from periodic to line-tied, from fully ionized plasmas to partially ionized plasmas, from local electron dynamics to global MHD physics. A next generation experiment with a device diameter of 3 m and length of 4 m, with enhanced field strength and heating power, can increase the normalized size (λ) by a factor of 3-6 and Lundquist number (S) by a factor of 8-50. Preliminary estimates show that, for anti-parallel reconnection, $\lambda \sim 100$ and $S \sim 5000$, and for guide field reconnection, $\lambda \sim 1{,}000$ and $S \sim 33{,}000$ (using reconnecting field) can be achieved. The new reconnection regimes shown in Fig.1 are within the reach by these numbers. In addition, the number of internal coils and electrodes can be increased to control connection better and to provide necessary flexibilities for reconnection studies in new geometries more relevant to heliophysics, such as interacting, line-tied plasma arcs. Measurements with high spatial resolution and wider coverage (to allow the capturing of reconnection at multiple X-lines) would be required. Additionally, non-perturbative diagnostics are desirable. The estimated construction costs are $5-10M over 2 years and operational costs are $2.5-3M per year. The main goals of this concept are

1. To study new regimes of multiple X-line reconnection directly relevant to heliophysical plasmas
2. To study particle acceleration in multiple X-line reconnection regimes
3. To study global impulsive relaxation, and the effect of non-periodic boundary conditions

Another example idea for a next generation experiment is based on Versatile Toroidal Facility (VTF) [43]. VTF is a small experiment dedicated to study fast reconnection in collisionless plasmas with a strong and variable guide field. Many important results [11,14,26,44] have been obtained on particle dynamics, micro-turbulence, and reconnection 3D onset, and have been successfully applied to understanding satellite observations. The parallel electric field required for the electron pressure anisotropy can provide effective dissipation energizing super thermal electrons. This particular mechanism of dissipation and associated particle acceleration can be studied by a next generation reconnection experiment with the estimated device diameter of 5 m and length of 2 m, with a series of internal coils which can be controlled to drive reconnection. In addition, multiple island interactions can be also studied as another source of super thermal electrons. The main goals of this concept are

1. To study electron pressure anisotropy near the X-line and associated particle acceleration in collisionless plasmas
2. To study the reconnection onset as a consequence of 3D dynamics

In addition to these new ideas for the next generation reconnection experiments, experimental campaigns can be formulated to study specific reconnection issues in laboratory plasma experiments designed for other purposes, such as fusion experiments for the ion heating [e.g. 15,16] and for the global spontaneous relaxation [e.g. 25]. Basic plasma experiments, such as the Basic Plasma Science Facility (BaPSF) at UCLA, can also be used for the reconnection studies. The BaPSF has been utilized to study fundamental physics with relevance to reconnection, for example generation of solitary structures by electron beams [45] and the interaction of magnetic flux ropes [20]. The former Electric Tokamak at UCLA [46] has been modified with a novel plasma source to generate large volume, high beta, magnetized plasmas which could be used for investigation of a wide range of basic plasma phenomena as part of the BaPSF [47]. Given the potential for large plasma size and demonstrated plasma parameters (temperature, plasma beta, collisionality), this facility would be highly suitable for staging future campaigns on the physics of reconnection.

6. Relation with theory and modeling

As have been demonstrated in the past decade, theory and modeling has been playing increasingly important roles not only in understanding laboratory results but also in linking them to heliophysical observations. This will be even more true for the next generation reconnection experiments which should be guided by scoping simulation studies from their beginning. Therefore, a healthy theory and modeling program is also critical for the success of the next generation reconnection experiments.

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Abstract

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- Quantitative tests of Sweet-Parker model [3]. This classical reconnection model proposed in 1950s was not tested experimentally until late 1990s. Significant modifications were required for quantitative agreements with experiment.
- Two-fluid effects for fast reconnection [4,5]. Existence of a quadrupolar out-of-plane magnetic field was predicted numerically [6], consistent with space data [e.g., 7], but definite confirmation by 2D measurements was done in the laboratory with theoretically predicted dependence on collisionality.
- Detection of electron diffusion region [8,9]. Its thickness was measured accurately and compared directly with state-of-the-art 2D PIC simulations. The comparisons challenged modeling and provided physical insights that 3D physics might be important in explaining the remaining disagreements with data. Detecting and studying the electron diffusion region is a goal of the MMS mission.
- Microturbulence in current sheets [10-12]. Predicted theoretically, electrostatic fluctuations were detected for lower-hybrid drift waves or electron phase space holes, but electromagnetic fluctuations were surprises to theory [13].
- Potential well and electron kinetics [14]. With measurements and physics understanding of electrostatic potential around the X-line, one can quantitatively explain the measured electron distribution function near the Earth's magnetotail.
- Ion heating by reconnection [15,16]. It was found in the laboratory that increments of ion energy are proportional to square root of ion mass or ion temperature is proportional to the charge-to-mass ratio. These findings may help solve the ion heating problem in the solar wind.
- Flux rope dynamics [17-21]. In attempts to be relevant to the dynamics of coronal loops, several experiments were performed either in linear or curved geometries with line-tied boundary conditions. Equilibrium and stability of the line-tied current loops is being studied quantitatively and compared with theories [e.g., 22].

It is clear from these examples that well-controlled and well-diagnosed experiments play increasingly important roles in understanding reconnection phenomena in heliophysical plasmas.

3. Outstanding Issues for Magnetic Reconnection in Heliophysical Plasmas

Despite significant progress in reconnection research, there exist a number of outstanding issues to be addressed before a better understanding of reconnection phenomena in heliophysical plasmas can be achieved.

- How is the reconnection rate determined? *(The rate problem)* Although two-fluid effects (e.g. the Hall term) have been shown to facilitate fast reconnection, the required efficient dissipation within the electron diffusion region is still elusive, and micro-turbulence in the current sheet can contribute to the solution of this problem. How does magnetic reconnection take place in partially ionized plasmas, such as in solar chromospheres where neutral particles dominate? Recent observations by HINODE show that reconnection-like energetic activity is abundant in these partially ionized plasmas.

- How does reconnection take place in 3D? *(The 3D problem)* In addition to the 3D microturbulence within the reconnecting current sheets, there are situations where the magnetic field vanishes in isolated three-dimensional points, or so-called 3D null points. Magnetic reconnection around these 3D null points or null-null lines [23] is important for understanding complex dynamics of the general magnetic topology, such as flux transfer events in the Earth's magnetosphere [24].
- How does reconnection start? *(The onset problem)* Large-scale reconnection phenomena, such as solar flares, coronal mass ejections, or magnetic substorms, often manifest themselves as impulsive relaxation events. Laboratory experiments [25, 26] and some numerical models [e.g. 27, 28] also exhibit spontaneous reconnection. However, it is unclear under what conditions these spontaneous reconnection takes place or whether these conditions are universal.
- How are particles energized? *(The energy problem)* Reconnection mainly manifests itself as an energetic process of releasing magnetic energy to plasma particles, sometime in the form of a high-energy tail of distribution functions [29-31]. Understanding how this process occurs is a major challenge. In addition to the acceleration due to single X-line reconnection, interactive multiple X-lines reconnection may provide a solution to this problem [32,33]. Additional possibilities, such as shock-based reconnection models, may be important to generate energetic particles [34].
- How do boundary conditions affect the reconnection process? *(The boundary problem)* It is not self-evident that reconnection physics in periodic systems can be straightforwardly applied to space and solar plasmas which are always non-periodic, and often line-tied at their ends [35]. Determining effects of boundary conditions is important to understand reconnection in heliophysical plasmas.
- How to apply local reconnection physics to a large system? *(The scaling problem)* Even all above issues are completely understood, there still exists an important issue on how to translate physics in small systems to larger heliophysical systems. When the plasma size

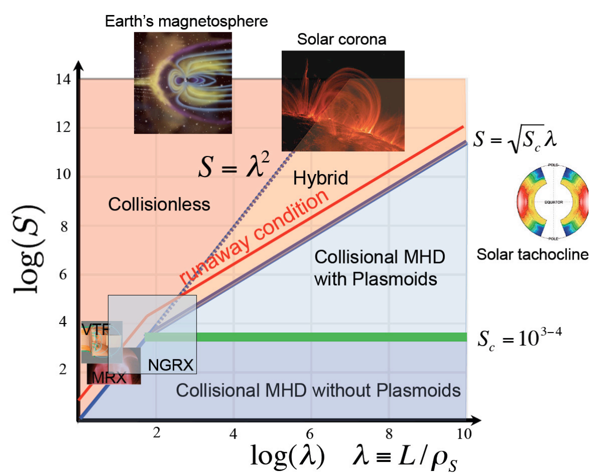

Figure 1. *A phase diagram for magnetic reconnection in 2D. If either S or the normalized size, λ, is small, reconnection takes place in collisional MHD (without plasmoids) regime or in collisionless regime. When both S and λ are sufficiently large, two new regimes appear: a regime for collisional MHD with plasmoids and a regime for collisional MHD plasmoids with kinetic current sheets in between. The regimes for reconnection in Earth's magnetosphere, solar corona, and solar tachocline are also shown. The existing experiments, such as MRX and VTF, do not have accesses to these new regimes while the next generation reconnection experiments (NGRX) should provide access to these relevant regimes for heliophysical plasmas.*

normalized by ion sound gyroradius, λ, and the Lundquist number, S, are sufficiently large, the reconnection physics derivates significantly from that either in small S or in small λ. A new phase diagram [36,37,28] emerged from recent large-scale numerical simulations [e.g., 38,39] as shown in Fig.1 where four reconnection phases are illustrated: collisional MHD without plasmoids, collisional MHD with plasmoids (corresponding to reconnection in solar tachocline), collisional MHD plasmoids with kinetic current sheets in between (or hybrid, corresponding to solar corona) and collisionless (corresponding to Earth's magnetosphere). In order to be directly relevant to reconnection phenomena observed in heliophysical plasmas, it is crucial for laboratory experiments to access all of these reconnection regimes. We note that reconnection in these new regimes is associated with multiple X-lines, and thus can possibly provide solutions to the onset problem and the energy problem mentioned above.

4. Existing laboratory experiments and their capabilities

Table I summarizes the capabilities by existing experiments for each issue listed above. With diversity in geometries and focus areas, these experiments are expected to continue to help address many of these outstanding issues into the next decades. Advancing in plasma diagnostics and interacting closely with observations, theory and modeling will continue to be a key. However, the critical issue of applying local reconnection physics leaned from these experiments to a large system, such as solar coronal plasmas, is difficult to be addressed due to the limited size and Lundquist number available in these experiments.

Issue	Existing Experiments	Opportunities for new Experimental Study
Rate	TS-3/4, MRX	Partially ionized plasma
3D	LAPD, MRX, SSX, VTF, Caltech	3D-null point
Onset	VTF	Global self-organization
Energy	3D-CS, LAPD, TS-3/4, MRX, SSX	Particle acceleration
Boundary	RSX, RWM, MRX, LAPD, Caltech	Non-periodic
Scaling	MRX	Large parameter space

Table I. *Outstanding reconnection issues addressed by the existing experiments and opportunities for new experimental studies.*

5. Opportunities and new ideas for next-generation reconnection experiments

Also listed in Table I are opportunities for new experimental studies in the coming decades for each outstanding issue. Among these, a major opportunity identified is to access the new reconnection regimes described in Sec. 3. Next generation experiments would therefore seek to achieve plasmas of normalized size on the order of 10^3 and Lundquist number on the order of 10^5 (see Fig.1). The physics of reconnection in these new regimes has more direct relevance with heliophysical plasmas than those already accessible by the existing experiments. With the capabilities to access these new regimes with multiple X-lines reconnection, the critical issues on particle acceleration, global impulsive relaxation, and non-periodic boundary conditions in a large system can be studied. Reconnection in partially ionized plasmas would be facilitated through larger plasma volumes. Shock-based reconnection models could also be tested more conclusively in larger plasmas.

New ideas for next generation experiments are emerging to meet these challenges. One example concept for such a next generation experiment is based on the Magnetic Reconnection Experiment (MRX) [40]. The MRX is a small experimental device dedicated for laboratory study of magnetic reconnection, using a set of specially designed internal coil assembles. Many significant results [3,4, 8,9,10,12,21,41,42] have been documented on a wide range of reconnection processes from collisionless to collisional, from periodic to line-tied, from fully ionized plasmas to partially ionized plasmas, from local electron dynamics to global MHD physics. A next generation experiment with a device diameter of 3 m and length of 4 m, with enhanced field strength and heating power, can increase the normalized size (λ) by a factor of 3-6 and Lundquist number (S) by a factor of 8-50. Preliminary estimates show that, for anti-parallel reconnection, $\lambda \sim 100$ and $S \sim 5000$, and for guide field reconnection, $\lambda \sim 1{,}000$ and $S \sim 33{,}000$ (using reconnecting field) can be achieved. The new reconnection regimes shown in Fig.1 are within the reach by these numbers. In addition, the number of internal coils and electrodes can be increased to control connection better and to provide necessary flexibilities for reconnection studies in new geometries more relevant to heliophysics, such as interacting, line-tied plasma arcs. Measurements with high spatial resolution and wider coverage (to allow the capturing of reconnection at multiple X-lines) would be required. Additionally, non-perturbative diagnostics are desirable. The estimated construction costs are $5-10M over 2 years and operational costs are $2.5-3M per year. The main goals of this concept are

1. To study new regimes of multiple X-line reconnection directly relevant to heliophysical plasmas
2. To study particle acceleration in multiple X-line reconnection regimes
3. To study global impulsive relaxation, and the effect of non-periodic boundary conditions

Another example idea for a next generation experiment is based on Versatile Toroidal Facility (VTF) [43]. VTF is a small experiment dedicated to study fast reconnection in collisionless plasmas with a strong and variable guide field. Many important results [11,14,26,44] have been obtained on particle dynamics, micro-turbulence, and reconnection 3D onset, and have been successfully applied to understanding satellite observations. The parallel electric field required for the electron pressure anisotropy can provide effective dissipation energizing super thermal electrons. This particular mechanism of dissipation and associated particle acceleration can be studied by a next generation reconnection experiment with the estimated device diameter of 5 m and length of 2 m, with a series of internal coils which can be controlled to drive reconnection. In addition, multiple island interactions can be also studied as another source of super thermal electrons. The main goals of this concept are

1. To study electron pressure anisotropy near the X-line and associated particle acceleration in collisionless plasmas
2. To study the reconnection onset as a consequence of 3D dynamics

In addition to these new ideas for the next generation reconnection experiments, experimental campaigns can be formulated to study specific reconnection issues in laboratory plasma experiments designed for other purposes, such as fusion experiments for the ion heating [e.g. 15,16] and for the global spontaneous relaxation [e.g. 25]. Basic plasma experiments, such as the Basic Plasma Science Facility (BaPSF) at UCLA, can also be used for the reconnection studies. The BaPSF has been utilized to study fundamental physics with relevance to reconnection, for example generation of solitary structures by electron beams [45] and the interaction of magnetic flux ropes [20]. The former Electric Tokamak at UCLA [46] has been modified with a novel plasma source to generate large volume, high beta, magnetized plasmas which could be used for investigation of a wide range of basic plasma phenomena as part of the BaPSF [47]. Given the potential for large plasma size and demonstrated plasma parameters (temperature, plasma beta, collisionality), this facility would be highly suitable for staging future campaigns on the physics of reconnection.

6. Relation with theory and modeling

As have been demonstrated in the past decade, theory and modeling has been playing increasingly important roles not only in understanding laboratory results but also in linking them to heliophysical observations. This will be even more true for the next generation reconnection experiments which should be guided by scoping simulation studies from their beginning. Therefore, a healthy theory and modeling program is also critical for the success of the next generation reconnection experiments.

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Strengthening Heliophysics Through Coordinated Plasma Astrophysics Programs With Laboratory Plasma Physics and Astrophysics

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This white paper introduces scientific opportunities articulated by a grass-roots community activity, called Workshop on Opportunities in Plasma Astrophysics or WOPA. The WOPA activity was initiated in summer 2009, and the workshop was held in January 2010, the workshop report was released in October 2010. The WOPA participants were organized into 10 working groups, each focusing on a particular plasma process important to heliophysics and astrophysics. The membership of each working group is roughly equally divided between three communities (laboratory plasma physics. heliophysics, and astrophysics), between theory/modeler and experimenter/observer, and between institutions. 10 major plasma astrophysics questions emerged from this activity, and have been highlighted in the report. We note that 8 out of 10 plasma processes are directly relevant to heliophysics:

- Magnetic reconnection
- Collisionless shocks and particle acceleration
- Waves and turbulence
- Magnetic dynamos
- Interfacial and shear instabilities
- Angular momentum transport
- Magnetized dusty plasmas
- Radiative hydrodynamics,

and the opportunities on each of these processes are described in a chapter of the WOPA report. It was recommendation that the plasma astrophysics programs in the U.S. be strengthened in structure and coordination across DOE , NSF, and NASA, to embrace the unity, coherence, and opportunities of the field. A strengthened program of plasma astrophysics should greatly aid the missions of these agencies, including NASA Heliophysics Division. The full report can be downloaded from the WOPA website:

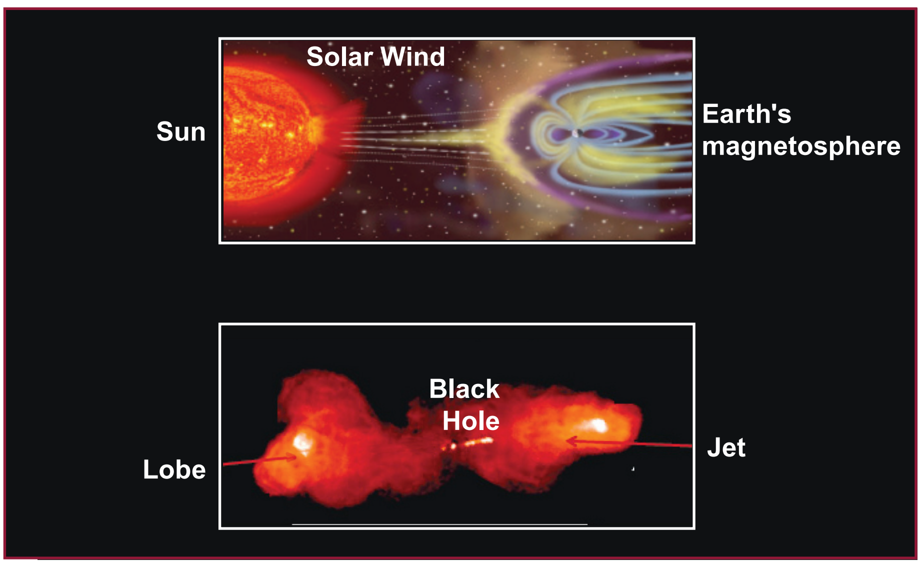
http://www.pppl.gov/conferences/2010/WOPA

and the Executive Summary is attached to this white paper.

EXECUTIVE SUMMARY

INTRODUCTION

Plasma pervades the universe at all measurable scales. At the very small scale, coupled processes in plasmas determine the behavior of the solar system. The Sun rotates, generates magnetic fields, and ejects mass in part because of plasma processes. The ejected plasma expands as the solar wind toward the Earth, becoming turbulent and hot as it travels. It then encounters and becomes trapped in the Earth's magnetic field, causes shocks, and produces magnetic substorms, aurora, and other plasma phenomena. This Sun-Earth system spans the short distance of 10^{-4} light years. Jumping ten orders of magnitude in size, extra-galactic jet systems are among the largest plasma structures in the universe. They begin with a rotating, accretion disk surrounding a supermassive black hole. Plasma transport processes determine the rate of accretion of matter onto the black hole, while producing the most luminous source of energy in the universe. The rotating plasma also launches a collimated jet that travels distances in the range of one million light years, ending in confined lobes of plasma. Dynamics of astrophysical systems at all scales between the solar system and jets are similarly regulated by plasma physics.



Plasma structures span all spatial scales in the universe, from the small scale of the solar system (shown in the top figure as an artist's sketch of solar wind spanning ~10^{-4} light years) to the large scale of extra-galactic jets, ~10^{6} light years (shown in the bottom figure from observation).

The study of plasmas beyond the Earth's atmosphere is here denoted as *plasma astrophysics*. This definition encompasses the usual realm of astrophysics (beyond the solar system), but also the domain of space physics (the Sun, the Heliosphere, and the magnetospheres of the Earth and the planets). The power of plasma astrophysics is that the same fundamental plasma processes appear in many different venues. For example, magnetic reconnection can drive not only magnetic substorms in the Earth's magnetosphere, but also flares on the surfaces of distant stars. The usual distinction between astrophysics and space physics disappears when viewed through the unifying lens of plasma physics.

Plasma astrophysics is positioned for rapid advance resulting from huge strides in astronomical observations, plasma technology, diagnostics, and plasma computation, combined with the maturity of plasma physics. Satellite and ground-based observations are set to measure plasma processes long invisible to us, from the solar interior to accretion disks. In-situ measurements of local plasma properties, including both field and particle information, have been expanded into every corner of our solar system: Earth's magnetosphere, the solar wind, other planets' magnetospheres, and the boundaries of our solar system. Multiple, coordinated satellites have greatly improved spatial and temporal resolution of magnetospheric measurements. Remote-sensing observations from both space and ground have moved beyond the traditional visible wavelengths to almost every wavelength band from far infrared emission from cold, partially ionized plasmas during star formation, to hard X-ray emission from extremely hot relativistic plasmas around supermassive black holes. High-power lasers now produce new plasma regimes with high energy density. These laser-produced, warm or hot, dense plasmas are similar to the interiors of giant planet cores and to the plasma that surrounds compact objects.

Plasma diagnostics can now measure, often remotely and non-perturbatively, a huge range of key particle and field quantities in the laboratory, both at the large scale and the small scale characteristic of turbulence. Modern techniques include laser scattering, laser-induced fluorescence, laser Faraday rotation, active spectroscopy using injected neutral atoms, miniaturized insertable probes, and electron cyclotron imaging techniques, to name a few. These provide new windows to detailed properties of magnetic fields, electric fields, electron and ion densities, plasma flow, and aspects of particle distribution functions. Advances in computation are revolutionizing how we study the complex behavior of plasmas. The surge in available computational power is being coupled with expansion of physics captured in computational models. Many plasma phenomena are governed by coupling between the large scale of the plasma system and the small scale characterized by microscopic plasma quantities (such as the particle gyroradius). New computational models can now treat this coupling, whether in multi-fluid treatments or new approaches that solve kinetic equations.

The opportunities represented by these technical advances can only be fully realized through a coordinated effort that brings together the communities of astrophysicists and laboratory plasma physicists. These communities involve observers, laboratory experimentalists, theorists, and computational physicists. Recent years have seen very significant beginnings of such coordinated efforts.

These beginnings indicate the large potential for accelerated progress and the need for an articulation of the major scientific challenges and opportunities in plasma astrophysics. Such an articulation would also express the unity and coherence of plasma astrophysics as a scientific discipline. Since it merges multiple areas of expertise, its unity can be overlooked, as reflected in the absence of a clear funding home for plasma astrophysics in the U.S.

To express the challenges, opportunities, and coherence of plasma astrophysics, more than 100 scientists were involved in preparing and participating in the Workshop on Opportunities in Plasma Astrophysics held in January 2010. The workshop, preceded by preparatory efforts of ten topical working groups, was a grass-roots effort organized by the plasma astrophysics community.

This effort brought together observers, experimentalists, computational plasma physicists, and theorists from universities, national laboratories, government research institutions, and private industry, including several scientists from outside the U.S. It also encompassed physicists studying magnetized plasmas and those studying high energy density plasmas. The breadth of participation uncovered cross-cutting opportunities previously unappreciated. This document reports the results from the workshop.

MAJOR QUESTIONS AND TOPICS

There are two approaches to articulating the challenges and opportunities: through plasma processes or through astrophysical systems. Individual plasma processes affect multiple systems, and individual systems encompass multiple processes. We have taken both approaches. Each of the ten working groups focused on one of the following processes that express the physics challenges (listed here in random order):

- Magnetic reconnection
- Collisionless shocks and particle acceleration
- Waves and turbulence
- Magnetic dynamos
- Interface and shear instabilities
- Angular momentum transport
- Dusty plasmas
- Radiative hydrodynamics
- Relativistic, pair-dominated and strongly magnetized plasmas
- Jets and outflows

Discussion of these topics, and their links to astrophysics, constitutes the bulk of this report. From these studies, we then extracted ten major, system-based questions for plasma astrophysics (listed here in random order):

How do magnetic explosions work?
Astrophysical plasmas exhibit spontaneous "explosions," such as solar flares, stellar flares, and substorms in planetary magnetospheres. These events accelerate particles to high energy, and affect radio communications on Earth. The explosions are driven by magnetic reconnection, the physics of which must be unraveled to understand why energy contained in magnetic fields of stars and planets is released explosively, and how this energy is so efficiently converted to particle energy.

How are cosmic rays accelerated to ultra-high energies?
Energetic particles bombard the Earth from space with energies up to 10^{20} electron volts, enormously more energetic than those achieved in the most powerful accelerator in the laboratory.

The energy spectrum of the particles fits a power law, yet the source of the strong acceleration remains a mystery. Possible sources include plasma shocks initiated by supernova explosions, as well as magnetic reconnection and plasma turbulence.

What is the origin of coronae and winds in virtually all stars, including the Sun?
Most stars have hot coronae with temperatures exceeding a million degrees. A hot wind blows from the Sun into the interstellar medium. A major challenge is how these nearly collisionless plasmas can be heated by waves, turbulence, shocks, and magnetic reconnection. This challenge requires advances in understanding the nature of the anisotropic turbulence in these plasmas.

How are magnetic fields generated in stars, galaxies, and clusters?
The universe appears to be magnetized at nearly all observable spatial scales. Stars, galaxies, galaxy clusters, and generally accretion disks, all contain magnetic fields. The fields often vary in time, sometimes in cycles. Understanding the origin and dynamics of these fields is a major puzzle, and is key to explaining accretion, stellar evolution, and galaxy evolution. The behavior of the fields depends on the plasma physics of dynamos, turbulence, reconnection, and flows.

What powers the most luminous sources in the universe?
The accretion of matter onto supermassive black holes generates prodigious fluxes of radiation, so intense that radiation pressure can dominate gravity. Understanding this process, which underlies the most luminous sources that light up the universe, is a challenge in plasma physics. Accretion is sufficiently rapid that it must involve plasma processes that enhance the accretion rate, such as plasma instabilities, turbulence, and transport.

How is star and planet formation impacted by plasma dynamics?
Despite progress in understanding star formation, the role of magnetic fields, especially in angular momentum transport, are still not understood. How rotating gas, plasma, and charged dust lose their angular momentum to collapse to form stars and planets remains an unsolved problem. Answers to this problem require advances in the physics of dusty plasmas, magnetic reconnection, and magnetized turbulence.

How do magnetic fields, radiation, and turbulence impact supernova explosions?
Supernovae and gamma-ray bursts are nature's grandest explosions that originate from the collapse of massive stars. Recent observations suggest that these explosions may be highly anisotropic and may be turbulent. Investigating the roles of magnetic fields, radiation, and turbulence on the explosions is a fundamental challenge. Magnetic fields are particularly important in the so-called magnetars.

How are jets launched and collimated?
Powerful jets of plasma are observed in a variety of astrophysical systems. They emanate from compact objects ranging from protostars to supermassive black holes, and can deposit large amounts of energy in the surrounding medium over large distances. Magnetic fields are believed to govern the process of jet formation and collimation. But it is not yet known how the jets are launched and why they survive stably across large distances (up to extragalactic scales). The behavior of jets encompasses a broad range of plasma phenomena, including instabilities, transport, dynamo, and reconnection.

How is the plasma state altered by strong magnetic fields?
When magnetic energy density is higher than the rest mass energy density of plasmas, the dynamics are altered significantly, as found in environments such as pulsars and relativistic jets. The ultra-strong magnetic field can produce electron-positron pairs, and alter plasma wind propagation and dissipation of plasma energy. Fundamental plasma processes, such as magnetic reconnection, are changed in these exotic environments.

Can magnetic fields affect cosmic structure formation?
Magnetic fields are observed in galaxy clusters, raising the question of whether the fields play a fundamental role in determining the topology and properties of these very large-scale structures. Magnetic fields may also be important in understanding the baryon dynamics in cosmic structure formation. These questions extend the applications of many of the basic plasma processes investigated at smaller scale to these new environments.

These questions are manifestly of major significance in astrophysics. What might not have been so obvious is that their answers largely reside in plasma physics. This report is dedicated to describing the challenges, opportunities, and impact of the following plasma research areas (listed here in random order):

Magnetic reconnection — a change in the topology of magnetic fields in plasmas — can drastically alter plasma transport and plasma structures, as well as convert magnetic energy to particle energy. Reconnection is thought to be everywhere in the universe, particularly underlying processes such as stellar flares.

Collisionless shocks accompany explosive events, such as supernova, and can accelerate particles to high energies. The behavior of shocks, and dissipation of their energy, in astrophysical plasmas in which collisions between particles are rare, is quite different and more complex than for the better-understood case with strong collisions.

Plasma turbulence is ubiquitous since most astrophysical plasmas have substantial free energy — such as nonuniformities in density, temperature, fields, and velocity space distributions — to excite turbulence. Turbulence affects the macroscopic behavior of plasmas in many ways, and has profound influences on essentially all the astrophysical questions articulated above.

The *dynamo* problem has long been a major astrophysical puzzle: how does the mechanical energy associated with a flowing plasma give rise to large scale magnetic field growth from a small seed field? This question is motivated by the prevalence of magnetic field in the universe. The dynamo problem also encompasses the questions of how magnetic field is sustained in the presence of dissipation, and why it varies in time in various astrophysical venues.

Interface and shear instabilities arise in both high energy density plasmas and magnetized plasmas in the presence of sheared flow. Their onset, behavior, and nonlinear development underlie a wide range of astrophysical phenomena including stellar wind flow around planetary and pulsar magnetospheres, the transitional region from solar wind to the interstellar medium, photoevaporated molecular clouds, supernova explosions, and blast waves in supernova remnants.

Momentum transport in plasmas is often observed to occur at a rate faster than can be explained from viscosity due to collisions between particles. Believed to be driven by plasma instabilities or turbulence, an explanation of momentum transport is required to understand how rotating matter collapses into gravitational potential wells. This question is key to understanding the accretion of matter onto compact objects (from protostars to black holes), the formation of stars, and the formation of planets.

Dusty plasmas consist of relatively massive charged dust particles, and thereby have properties altered from the conventional plasma of lighter ions and electrons. As breeding grounds for planets and stars, dusty plasmas have influence at both the solar system and galactic scales.

Radiation hydrodynamics — the interaction of radiation with matter — introduces an additional player (radiation) to the plasma environment. It is important for the formation of the largest stars (through photo-ionization and heating of the gas surrounding young stars), the behavior of accretion disks (when radiation pressure is substantial), the structure of molecular clouds (due to photoevaporation), the atmospheres of extrasolar planets (influenced by radiation from stars), and supernova explosions of massive stars (where radiation pressure exceeds material pressure).

Relativistic, pair-dominated and strongly magnetized plasmas are somewhat exotic systems that are ubiquitous in the high energy universe. When particles are moving at relativistic speeds, when electron-positron pairs dominate the plasma (rather than electrons and ions of unequal masses) and when the magnetic field is ultra-strong (altering collisions, ionization, radiation, and atomic structure), the behavior of the plasma changes significantly. These conditions can occur in violent astrophysical phenomena such as pulsar winds, gamma-ray bursts, jets in active galactic nuclei, microquasars, neutron star atmospheres, and the first few seconds of the early universe.

Jets and outflows represent a type of plasma structure whose formation and behavior challenges many aspects of plasma physics. They are observed to emanate from a wide range of compact objects, and might have a significant impact on cosmic structures.

These ten topics in plasma physics are separately described in the chapters that follow. The opportunities articulated in this report both advance research in plasma topical areas and lead toward resolution of the major astrophysical questions cited earlier.

IMPACTS AND CONCLUSIONS

These research opportunities will additionally have impact in three areas beyond these targeted major questions. First, much of the physics overlaps with central challenges for fusion energy, both magnetic and inertial (the purview of the DOE). For example, in magnetically confined plasmas, magnetic reconnection drives sawtooth oscillations and disruptions in tokamaks, momentum transport determines the rotation of toroidal plasmas, plasma turbulence regulates transport in nearly all magnetic fusion plasmas, and particle acceleration and heating by waves and instabilities occurs both deliberately and spontaneously. In inertially confined plasmas, Rayleigh-Taylor instabilities influence the symmetry of implosion and radiative hydrodynamics influences the burn phase. Many of the advances in plasma astrophysics have evolved directly from plasma physics developed for fusion energy, and plasma physics learned through astrophysical applications is increasingly influencing aspects of fusion plasma physics. Second, development of plasma physics targeted to astrophysics advances basic plasma physics (the purview of the NSF and DOE). The wide range, sometimes extreme, of scales, particle energies, field strengths, and overall plasma parameters encountered in astrophysics extend greatly the scope and depth of plasma physics. Third, plasma astrophysics is crucial to the guidance and interpretation of observational missions (the purview of NASA). From satellite observations of the magnetosphere to the heliosphere and other galaxies, guidance from plasma astrophysics is needed to determine what quantities to measure and to make scientific sense of those measurements. And for some missions, the primary goal is to directly study a particular plasma process. That is, plasma astrophysics is needed in the preparation stage of missions, to optimize its value, and in the operational stage, to reap the benefits. For example, understanding aspects of magnetic reconnection, waves, and turbulence is essential to the success of the Magnetospheric Multiscale Mission, the Solar Dynamics Observatory, the Solar Orbiter, and the Solar Probe Plus. Understanding aspects of accretion and particle acceleration is key to reap the full benefit of the Nuclear Spectroscopic Telescope, the James Webb Space Telescope, Large Synoptic Survey Telescope, Atmospheric Čerenkov Telescope Array, and the International X-ray Observatory.

The report articulates many general and specific research opportunities. The content of each of the following chapters was written by a topical working group (see Appendix D for a list of the membership of each working group). Being a community report, no effort is made to rank the many opportunities that for each area were developed by the specific topical experts. That exercise is beyond the province of this activity. Thus, this report produces no recommendations except one. We recommend that the plasma astrophysics program in the U.S. be strengthened in structure and coordination across DOE, NSF, and NASA, to embrace the unity, coherence, and opportunities of the field. A strengthened program of plasma astrophysics greatly aids the missions of these agencies. One intention of this report, in addition to the immediate scientific value of the effort, is to provide motivation and justification for deeper consideration of the funding strategy for plasma astrophysics.

Heliospheric Particle Explorer: Advancing our Understanding of Magnetospheric, Solar Energetic Particle, and Cosmic Ray physics

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1 Introduction

We propose a low earth orbiting satellite with an instrument payload that measure energetic particles over a wide range of energies and species. Charged particles (electrons, protons and heavy ions) in space provide a window into the physical universe encompassing a wide variety of phenomena covering low energy plasmas to highest energy cosmic rays. The proposed mission will address important science science questions in the domains of terrestrial radiation belt dynamics, solar energetic particles, Jovian electrons and cosmic rays. The proposed mission is based on heritage deriving from the very successful NASA mission, SAMPEX (Solar Anomalous Magnetospheric Particle EXplorer) *but extends in a very substantial way the instrument capabilities and mission parameters* thereby enabling significant advances in our scientific understanding of energetic particle dynamics in the heliosphere. The proposed mission spans multiple sub disciplinary areas of research addressing the Sun-Earth system and is a low cost platform worthy of serious consideration for the next decade.

2 Mission Concept

We propose a low Earth orbiting spacecraft carrying instruments capable of measuring charged particles, viz., electrons, protons and ions to advance the scientific knowledge of

i relativistic electron dynamics in the Earth's radiation belts,

ii solar energetic particle sources, acceleration, and propagation, and

iii Jovian electrons and cosmic ray modulation.

The proposed science payload will comprise state of the art instrumentation specifically designed to address the key science topics and will measure particle fluxes, species, and energy spectra with high temporal and spatial resolution. These measurements will significantly further the understanding of relativistic electron dynamics and charged particle acceleration and propagation processes at the Sun and in interplanetary space. Onboard instruments will measure electrons with an energy resolution of $\frac{\Delta E}{E} \approx 20\%$ covering an energy range extending from $\approx$ hundreds of keV to tens of MeV. Additionally high time resolution modes will fully characterize electron microbursts, an important loss mechanism. Measurements of SEP ions will span energies ranging from $\approx$ 1 MeV/nuc to about 100 MeV/nuc and with $1 \leq \mathrm{Z} \leq 28$. The data and science analyses from this mission will complement upcoming in-situ observations of energetic ions in the inner heliosphere.

2.0.1 Mission Overview

The mission we propose will be in a high inclination low earth orbit, e.g., with an altitude of about $\approx$ 600 kms and $\gtrapprox 85°$ latitude which will accomplish two important tasks; that of covering all L shells and sampling the Earth's polar regions which have open field lines connecting to the interplanetary space. At these altitudes the orbital period is expected to be about 90 minutes, visiting each L shell about four times in an orbit. The spacecraft orbit will be the sun synchronous dawn-dusk plane. The science payload (described in Section 4) will comprise charged particle sensors with appropriate geometry factors, energy and temporal resolution required to achieve the science goals. The chosen orbit will provide enhanced capabilities for the study of radiation belt dynamics,for example, by covering the magnetospheric regions dominated by EMIC waves (dusk) and Chorus (dawn) waves. These waves are currently thought to be implicated in loss and energization of relativistic electrons. Since in this orbit, the spacecraft will spend sufficient time over the polar regions thus enabling studies of SEP, Jovian electrons and cosmic rays.

3 Science Gains

The proposed mission will lead to significant advances in our understanding of several key areas of the Sun-Earth system dynamics. The science aspects addressed include, relativistic electron dynamics in the Earth's outer zone, solar energetic particle sources and acceleration processes, and charged particle propagation in the heliosphere. In addition important space weather aspects such as spacecraft anomalies due to deep dielectric discharge, potential hazards to humans in space due to lowered cosmic ray and SEP cutoffs are additional capabilities of the the proposed mission. These topics and the measurements that enable their achievement are summarized briefly below :

- **Radiation belt dynamics**
  - relativistic electron acceleration processes are addressed by the capability of measuring spectral evolution with a high energy and time resolution
  - relativistic electron loss mechanisms due to wave-particle interactions can be characterized by our measurements of microbursts and pitch angle resolution.
  - high time resolution continuous monitoring of the relativistic electron fluxes covering the entire outer zone to asses deep dielectric discharge.
- **Solar Energetic Particles**
  - charge states by utilizing the Earth's magnetic field as a spectrometer.
  - neutral atoms.
  - cutoffs during geomagnetically disturbed times
- **Jovian electrons, and Cosmic Rays**
  - particle transport in the inner heliosphere
  - solar modulation of cosmic rays

3.1 Radiation belt dynamics

The proposed mission in a low Earth polar orbit has a major advantage of being able to sweep across all L shells of the outer zone in a relatively short time. Earlier missions, chiefly SAMPEX have used this advantage and have provided valuable insights. However we note that the instruments onboard SAMPEX were not designed to study radiation belts and had severe limitations such as lack of detailed spectral information, and pitch angle distribution. Furthermore, the PET (Proton Electron Telescope) detector used extensively for radiation belt studies suffered from major contamination due to chance coincidence and count rate saturation. The instrument proposed here to address radiation belt dynamics is designed to provide high quality measurements specifically addressing radiation belt dynamics, for example, the instrument will

- measure electron spectra in multiple differential channels (energy resolution, $\frac{\Delta E}{E} \approx 20\%$)
- be optimized to minimize background, chance coincidence and misidentification
- enable the separation of trapped and precipitating electron fluxes

As described below (see Section 4) the solid state telescopes on board the proposed mission will have a high time resolution mode in order to fully characterize relativistic electron microbursts.

3.1.1 Characterizing electron energization

The proposed mission will measure electron spectra and their temporal evolution and will therefore be able to characterize electron energization. Details such as spatial extent, degree of spectral hardening can be measured reliably and accurately to help delineate the underlying physical mechanisms. As shown by *Kanekal et al.* [2001]; *Kanekal et al.* [2005] there is a degree of global coherence that implies low altitude measurements capture the dynamics of the relativistic electrons with high fidelity.

Figure 1 shows electron spectra during a geomagnetic storm from days prior to the day of minimum D_{st} (doy 239; -200 nT) to those during the recovery phase. This storm resulted in a strong relativistic electron flux enhancement event. The spectra were measured by the HIST sensor onboard the Polar mission. We note that the measurements by Polar had a low temporal resolution due to its orbit. The proposed mission will have a higher time resolution (≈ 90 minutes) which is needed to discriminate between various electron energization mechanisms. The fast sweep of L shells combined with spectral measurements has the potential to investigate important aspects of energization, such as the temporal and spatial relationship of a seed population to that of the energized fluxes, response of the magnetosphere as a whole to solar wind energy input (*Vassiliadis* [2008]), and characterization of the dependence upon diverse interplanetary drivers. In addition electron losses (see next section) will also be characterized and thus enable a fuller and complete understanding of electron dynamics which is of course a result of the balance between energization and loss.

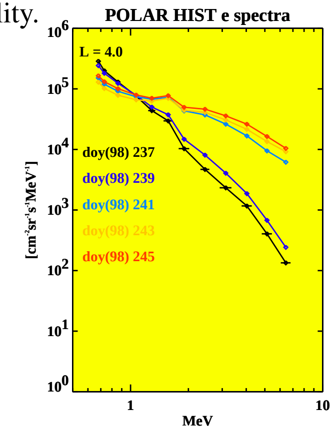

Figure 1: Evolution of electron spectra.

3.1.2 Characterizing electron losses

Relativistic electrons are lost by precipitation, and movement out of the magnetosphere, e.g., magnetopause shadowing. Wave particle interactions are thought to be the leading cause of electron precipitation (reviewed recently by *Millan and Thorne* [2007]). The proposed mission can advance our knowledge of both slow and steady loss of the type resulting in global coherence (*Kanekal et al.* [2005]) as well as rapid loss through electron microbursts.

Figure 2 shows count rates of relativistic electrons during a radiation belt pass as seen by the HILT sensor onboard SAMPEX. The microbursts are seen as rapid fluctuations in electron count rates in a region from L$\approx 3 - 6$ (*Lorentzen et al.* [2001]). These microbursts are thought to constitute a significant mode for the loss of relativistic electrons and have been estimated to be capable of draining significant fluxes of electrons (*O'Brien et al.* [2003]). A full and detailed characterization of the microbursts would include spectral,spatial and temporal aspects of these events. All these have important bearings upon the physics of electron loss, for example, spatial characterization of microbursts reveals the spatial extent of the wave-particle interactions causing electron precipitation. The proposed mission with the instrument suite described is ideally suited for characterizing microbursts.

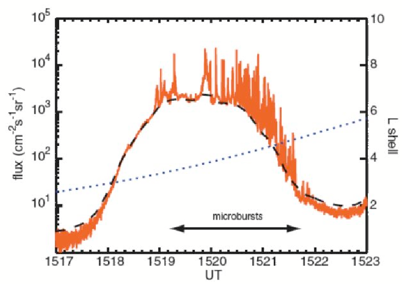

Figure 2: electrons > 1 MeV microbursts on October 19, 1998 (adapted from *Lorentzen et al.* [2001]

3.2 Solar Energetic Particles

Solar energetic particles provide important information regarding the dynamic nature of their source, i.e, the Sun and the interplanetary medium through which they travel. Their study is important not only from a scientific perspective but also from a space weather point of view. The mission we propose is ideally suited to study SEP acceleration, transport and their impact on humans in space. The solid state particle telescopes onboard the proposed mission (see Section 4) measure electrons, protons and ions over a wide range of energies with excellent energy resolution.

3.2.1 Charge States of Solar Energetic Particles

Measurements obtained over the last decade have shown a large variability of the mean ionic charge of heavy ions in solar energetic particle (SEP) events (e.g., *Klecker et al.* [2007]). This variability is due both to source populations and to variable conditions during acceleration and propagation. For example, the mean ionic charge in impulsive (electron-rich, 3He-rich and Fe-rich) events is strongly energy dependent and increases for Fe from 11-15 at 0.1 MeV/nucleon to 16-20 at 0.5 MeV/nucleon *DiFabio et al.* [2008]. This can only be explained by charge stripping in a sufficiently dense environment during acceleration, placing the acceleration region in the low corona (e.g. *Kartavykh et al.* [2007]). In large (gradual) SEP events where the intensity increase of energetic particles in interplanetary space is related to coronal and interplanetary shocks, the ionic charge at low energies ($<$ 1 MeV) is compatible with solar wind charge states (e.g. Q $\sim$10 for Fe, *Klecker et al.* [2008]), suggesting a solar wind origin. At energies above 10 MeV/nuc, also high charge states (Q $\sim$20 for Fe) are often observed (e.g. *Labrador et al.* [2003]), indicating the contribution of different particle sources to the energetic ions observed in interplanetary space. These results illustrate that the determination of the ionic charge of SEPs is essential for the understanding of composition and energy spectra of SEPs that generally will depend on the particle source, and on acceleration and propagation conditions, that in turn depend on the ionic charge of the particles.

We note that there are no instruments for the in-situ determination of the ionic charge of energetic ions included in the upcoming missions such as the Solar Orbiter and Solar Probe Plus that cover the time period of the decadal Survey 2013-2022. The measurement of the ion parameters energy and mass, together with the determination of the geomagnetic cutoff in a low altitude polar orbit, allows the determination of the ionic charge of solar energetic particles. This technique was successfully used on the SAMPEX spacecraft (*Mason et al.* [1995]; *Leske et al.* [1995]) and allowed for the first time the direct determination of the ionic charge of anomalous cosmic rays (*Klecker et al.* [1995]), and the determination of SEP ionic charge states over the extended energy range of 0.3 to 70 MeV/nuc (*Oetliker et al.* [1997]).

3.2.2 Neutral atoms

Recent observations by *Mewaldt et al.* [2010] have characterized neutral hydrogen related to a flare/CME event and created by proton acceleration at interplanetary shocks. The authors summarized that these neutrals have the potential to advance scientific understanding of solar particle acceleration. From the vantage point of LEO where the geomagnetic field acts as a shield to charged particles, so that the observations of neutral hydrogen are relatively free of background from protons. A dawn-dusk orbit as proposed would have $\gtrsim$ 50% duty cycle (due to Earth limb shadowing) and over the life cycle of the mission may be expected to gather a fair number of events. In conjunction with other missions imaging the Sun, these *ENA images* may be compared to CME images to obtain insights into the nature of solar neutrals.

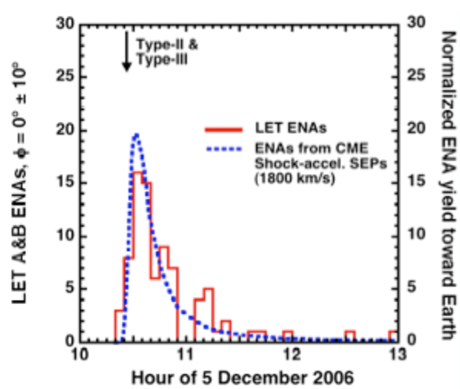

Figure 3: Neutral hydrogen from the Sun (from *Mewaldt et al.* [2010]).

3.2.3 Cutoff variability and trapping

Charged particle cutoffs vary considerably during geomagnetically disturbed times constituting a serious hazard to humans and human assets in space. Figure 4 illustrates the observed proton cutoff variability during a geomagnetic storm (November 1997). Lowered cutoffs expose humans and human assets to radiation hazards and monitoring them is an important aspect of space weather. Furthermore, the correlation between the cutoff location and the D_{st} index at times shows cutoffs being lowered prior to D_{st} decrease *Kanekal et al.* [2005]; *Leske et al.* [2001].

Thus apart from important space weather aspects there are additional scientific issues that need to be addressed. At times, SEPs penetrate deep into the magnetosphere and get trapped resulting in the formation of new belts which can last from days to months.Details of the physics of the trapping and the role of the interplanetary drivers remain yet to be fully established. The proposed mission in high inclination LEO is ideally suited to carry out these measurements. The onboard charged particle instruments with optimized geometry factors, background suppression and temporal,spatial and energy resolution will significantly further our scientific understanding.

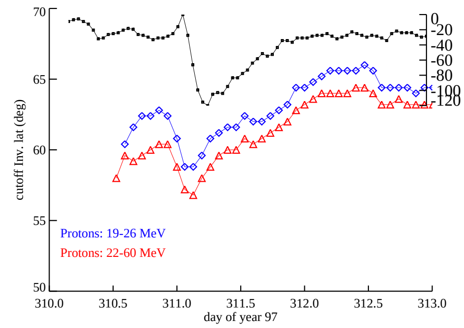

Figure 4: Proton cutoffs and D_{st}

3.2.4 Jovian electrons and cosmic rays

Jovian electrons can be observed over the Earth's poles and can provide information not only regarding the source *Kanekal et al.* [2003] but also about particle transport in the heliosphere, validation of solar wind models, interplanetary field twisting and turbulence *Owens et al.* [2010]. The proposed mission will also monitor cosmic rays during the next solar cycle. Considering the record high GCR intensity during the current unusually extended solar minimum, it will be of great interest to observe the solar modulation during the upcoming maximum. We note that the Voyager mission will measure the interstellar spectrum of ions which can be compared with observations made by the proposed mission to further the understanding of solar modulation. These science topics are well within the scope of the instrument proposed for this mission and increase its multi-disciplinary appeal.

4 Scientific Payload

Instrument Type	Measurement Characteristics	Science Goal
Solid state Particle Telescope (SST1)	$\mathbf{e}^{-} \gtrsim 2$ to $\gtrsim 10 MeV$ $\Delta E/E \approx 30\%$ $\mathbf{p} \gtrsim 15$ to $\gtrsim 70 MeV$ $\Delta E/E \approx 30\%$	rel. electron energization and loss, inner belt and solar protons
Solid state Particle Telescope (SST2)	$\mathbf{e}^{-} \gtrsim 0.1$ to $\gtrsim 4 MeV$ $\Delta E/E \approx 30\%$ $\mathbf{p} \gtrsim 5$ to $\gtrsim 20 MeV$ $\Delta E/E \approx 30\%$	rel. electron energization and loss inner belt and solar protons
Ion Composition Analyzer (ICA)	$1 \leq Z \leq 28$ ≈ 1 to ≈ 100 MeV/nuc	charge states energetic neutral atoms

Table 1: Proposed instrument suite.

The science payload comprises of charged particle sensors capable of measuring electron, protons and ions covering the appropriate energy ranges required to address the science goals. The details of the instrument energy ranges and resolution are spelled out in Table 1. The SST1 and SST2 sensors will have the additional capability on select energy channels to measure electron rates with a very high time resolution of the order of tens of milliseconds in order to characterize electron microbursts which result in loss of relativistic electrons. The higher energy sensor, SST1 will be modeled after the REPT (relativistic Electron and Proton Telescope) which will be flown on NASA's RBSP (Radiation Belt Storm Probes) spacecraft. However REPT does not have the high resolution capability and the RBSP orbit is unsuited for the study of microbursts. The payload will comprise two copies of each of the instruments oriented at right angles to each other. This will enable the SSTs to measure the trapped and the precipitating particle populations. One of the ICA units will be sun pointing and will be able to characterize solar neutral atoms (which of course do not follow the spiral interplanetary field). While charged particle telescopes are not a new technology, there is scope for innovation regarding the associated electronics and instrument configuration that makes them desirable on future missions. The proposed instrument suite is therefore appropriate for future missions considered by NASA and reviewed by this decadal survey.

5 Estimation of Mission cost

Table 2 lists estimated costs for the proposed mission. The instrument costs include design, development, building and calibration. We note that there are two copies of each instrument, one zenith pointing and the other looking toward the sun and perpendicular to the zenith. Launch costs depend upon whether a dedicated launch vehicle is used or piggybacked with another mission. The total mass of the payload and the spacecraft bus is estimated to be less than 200 kilos which can be launched on a pegasus. The instrument costs are based on our experience with RBSP/REPT, SAMPEX/MAST, ACE/SIS, STERO/LET and other instruments. Operational costs are extrapolated from our prior experience with SAMPEX and include software development for mission ops. as well as science data analyses. The estimated total mission costs are $\lessapprox$ \$150M which makes this a small sized mission.

Instrument Launch,Ops.	Total cost \$M	Additional Remarks
SST1	20	two units
SST2	20	two units
ICA	20	two units
s/c bus	50	dedicated
Launch	30	dedicated
	15	piggyback
Operational	5	per year

Table 2: Estimated mission costs.

6 Viability of the Proposed Mission

The proposed mission makes significant contributions to both the SWM and SHP panels addressing as it does, radiation belt response to solar wind and the characterization of SEPs. The study of radiation belt energization and loss, and understanding the acceleration and transport of charged particles in the interplanetary space are important scientific questions for the next decade and are ripe for significant advances. We note that the space weather component of the mission has important societal benefits as human exploration and human assets in space are expected to dramatically increase in the next decade. The proposed mission may be defined as *small* since its total costs are expected to be under \$150M and as such is eminently affordable. Moreover, the proposed instrument suite uses tried and true technologies while being flexible enough to accommodate new advances in solid state detector and associated electronics technologies. The mission can be ready in a reasonably short time span as it is technically straightforward and well within the expertise of major space science institutions in the country. Finally the proposed mission will very strongly complement both radiation belt missions such as the RBSP and interplanetary missions such STEREO.

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A NASA-funded CubeSat Program

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Executive Summary

We propose an augmentation of the Suborbital and Special Orbital Projects (SSOPD) program to include CubeSats as an available science and technology platform, to complement the existing sounding rocket and balloon platforms. A relatively modest increase in the SSOPD budget of ~ $12.5M would allow for a vibrant CubeSat program of up to 4 launches pear year, enabling flight demonstrations of new instrument concepts and opportunities for students to develop the specialized scientific, engineering and management skills required to maintain NASA as a preeminent space agency. The program could be managed at Wallops Flight Facility (WFF), paralleling the highly successful suborbital program, and could leverage the existing WFF contract with NSF to provide technical support for the NSF CubeSat program.

Motivation

For decades the NASA sounding rocket and balloon programs have, and continue to be, indispensable platforms for developing and nurturing the next generation of scientists and engineers, for testing and validating new technologies and instrumentation, and for offering rapid access to space for cutting-edge science experiments. The success and wide community support for the NSF CubeSat Program combined with the increasing number of NASA Explorer proposals that utilize CubeSats demonstrates the maturation of the CubeSat platform. The addition of CubeSats to the NASA portfolio of science mission platforms would enable significant new experiments for all branches of heliospheric and Earth science.

The current manifest of NSF CubeSat missions demonstrates that CubeSats can address a broad array of cutting edge science questions using state-of-the-art instrumentation:

Radio Aurora Explorer (RAX) / Hasan Bahcivan (SRI), James Cutler (University of Michigan) - Understanding the microphysics of plasma instabilities that lead to field-aligned irregularities (FAI) of electron density in the polar lower (80-300 km) ionosphere.

Dynamic Ionosphere CubeSat Experiment (DICE) / Geoff Crowley (ASTRA), Charles Swenson (USU) - Studying storm-time features of ionospheric plasma.

Firefly / Doug Rowland (GSFC), Allan Weatherwax (Siena College) - Determining the source of terrestrial gamma ray flashes.

Colorado Student Space Weather Experiment (CSSWE) / Xinlin Li (University of Colorado, Boulder) - Investigating the relationship between solar energetic particles, flares, coronal mass ejections, and Earth's radiation belts.

Focused Investigations of Relativistic Electron Burst Intensity, Range and Dynamics (FIREBIRD) / Dave Klumpar (Montana State), Harlan Spence (University of Hew Hampshire) - Resolving the spatial scale size and energy dependence of electron microbursts.

CubeSat for Ions, Neutrals, Electrons and MAgnetic fields (CINEMA); TRIO / Bob Lin (UCB), Kyung-Hee University (Korea) - Providing critical space weather measurements of Energetic Neutral Atom (ENA) and in situ suprathermal particles.

Each mission is funded at ~$900k over three years, a relatively small investment that provides for technology and instrument development and training a new generation of scientists and engineers, while simultaneously addressing compelling science questions. Given the continued and growing community support for CubeSats, the maturation of the necessary technology, and the demonstrated benefits to NASA and the heliophysics community, we believe it is time for NASA to include CubeSats as an option in the Suborbital and Special Orbital Projects program. For a small yearly investment NASA would enable:

A) **Instrument & technology test beds**. A major impediment to instrument development is the lack of flight opportunities in which to test and validate new designs. This problem is particularly acute for university researchers who often do not have the access to programs, such as Space Test Program (STP), that the labs do. The lack of inexpensive flight opportunities limits innovation, as new instruments are rarely able to improve the TRL level to the point they could be proposed. For certain types of instrumentation, sounding rockets provide flights of too short duration to test long term instrument or hardware performance, while balloons do not provide the necessary altitudes. CubeSats fill this void, opening a new realm of low-cost investigations, with instrumentation not appropriate for sounding rockets or balloons.

B) **Training the next generation of scientists and engineers**. The sounding rocket and balloon programs have been a primary means by which NASA has trained scientists and engineers for more expensive flight hardware development. Developing a vibrant, well-trained workforce is vital for the long-term health of NASA and the overall space program within the United States. A CubeSat program within the auspices of NASA would expand the explorable regimes of near-Earth space and open up a new realm of instrument development, including solar and terrestrial imaging, thermospheric and ionospheric in situ measurements, and remote sounding. Further, while the sounding rocket and balloon programs allow for often substantial student involvement in designing and building instrumentation, there are comparatively few opportunities to train component or systems engineers within an operational context. Space physics missions often require close collaboration between the scientists, instrument designers, and spacecraft engineers to achieve mission success. Spacecraft charging and magnetic cleanliness are just two examples where choices made in systems designs could adversely affect the ability to produce accurate scientific measurements. The field would be well served by bringing systems engineers through flights embedded in a space physics program. Because of their small size and low cost, CubeSats offer the ideal platform for student engineers to design, build and fly not just spacecraft subsystems but an entire integrated spacecraft.

C) **Focused science investigations**. As the NSF CubeSat program has demonstrated, the platform is fully capable of a range of science implementations across heliophysics, including ionosphere/thermosphere/mesosphere (ITM), solar and magnetospheric science. The flexibility of the CubeSat platform to be three-axis stabilized or spinning, for example, enables the full-breadth of heliophysics science to be explored. The low cost and complexity allows rapid turn-around from inception to launch, enabling rapid study of focused science questions and also valuable second-tier science that does not justify an Explorer class mission. For example, the NSF Firefly mission is designed to answer very specific questions about energetic electron acceleration over thunderstorms. Despite its small size, its instrumentation is focused to answer new questions that larger satellites, not expressly designed for this mission, could not answer. In a similar fashion to existing suborbital programs, a CubeSat program would allow relatively short concept-to-flight times. Typically, payloads can be flight ready in less than three years from concept and much less than that for existing science.

NASA has typically required closure or significant progress on science questions as a measure of the success of a space flight mission. We believe it would be a mistake to implement a CubeSat program with the same standards of science closure as, for example, the Explorer program. Instead, A NASA sponsored CubeSat program should be implemented to promote flight validation of new advancements, early cutting edges science results, and effective post graduate research, with the acceptance of some risk. A CubeSat experiment that fails early in orbit, for example, has still provided important technical, scientific and engineering development.

Technical Implementation

NASA could implement and manage a CubeSat program in a number of different ways. One option would be to mimic the sounding rocket approach, where much of the technical engineering infrastructure (e.g., communication, attitude control system (ACS), power, mechanical design, and deployment) lies at WFF, leaving the Principal Investigator (PI) responsible for the instrumentation. Another option is to mimic the current NSF implementation, where the PI is largely responsible for all aspects of the CubeSat. Each option carries distinctly different sets of advantages and disadvantages. Relying on WFF for engineering infrastructure frees the PI to focus on their instrument and science, without needing to “reinvent the wheel.” It allows for shared engineering designs and access to flight for small groups that do not have the engineering resources or expertise necessary to design, engineer and build a complete flight system. On the other hand, there is often tremendous value in having the PI and their team design and build a complete system. It allows for the training of systems and subsystem engineers, and can allow for greater flexibility and innovation in spacecraft design.

We describe below the details of implementing a CubeSat program under the auspices of the Suborbital and Special Orbital Projects Directorate (SSOPD) at WFF. This is but one example of an implementation of a NASA-funded CubeSat program, and we encourage the survey panel to examine others, including partnering directly with NSF on the existing program and implementing the NSF-style program within NASA. Regardless of implementation, the program should adhere to the spirit of the CubeSat platform, which is engineering and technical training combined with high science return on a small but powerful platform.

A CubeSat Program office at WFF

The Goddard Space Flight Center Suborbital and Special Orbital Projects Directorate (SSOPD) at WFF could manage the CubeSat Program for a relatively modest investment. SSOPD currently supports the National Science Foundation (NSF) CubeSat Program, manages the Advanced Technologies Program (ATP) for CubeSat and Unmanned Aerial Vehicle (UAV) Applications, the NASA Sounding Rocket (SR) Program and the NASA Balloon Program. SSOPD would manage the overall CubeSat program in a manner similar to the services currently provided in support of the NSF CubeSat Program. This will include coordination with NASA sponsors, interfacing with launch services, offering use of existing test, evaluation, and ground support infrastructure, management of CubeSat bus services, and coordination with selected CubeSat developers. The CubeSat Program would build on SSOPD's long history of successful implementation of NASA's sounding rocket and balloon programs with a culture of responsive schedules, low-cost methods, and miniature payload accommodations. It will also draw from the recent development of CubeSat systems, through the ATP for CubeSat and UAV Applications.

Today, the sounding rocket and balloon programs provide ease of integration for the science instrument developer. The CubeSat Program would be designed in the same fashion to make available to developers CubeSat technologies from the SSOPD ATP, although the proposer would have the option of pursuing their own spacecraft bus solutions. SSOPD has integration and test facilities tailored for small satellites, which will support CubeSat development and testing. These facilities include labs, clean rooms, thermal-vacuum chambers, vibration test stands, Electromagnetic Interference/Electromagnetic Compatibility (EMI/EMC) facilities, antenna pattern test facilities, and spin-balance test facilities. WFF could also provide ground station services.

The current balloon and sounding rocket programs enable the science community to select and prioritize mission funding through a program executive, simplifying the proposal and selection process. Program implementation management is executed through the WFF program offices that provide the integration and launch services. This allows the science PI to focus largely on the delivery of the science instrument should they choose. Typically the PI will have the option to employ extensive use of instrument support "bus" elements that can be provided by the program office. Examples of these are solar pointing for balloons or telemetry and attitude determination for sounding rockets. The CubeSat program could be implemented in very much the same way. This paradigm allows the proposers the flexibility, if they choose, to focus their limited resources solely on the instrumentation and science. In some cases an integrated spacecraft would be proposed.

As mentioned above, the vision is to provide a small program office at WFF that would be responsive to a program executive at HQ. Flight manifesting would be coordinated through the CubeSat Program Office. Through WFF civil servant and contract engineering, bus and ejector components, integration and test services would be arranged for and provided by the program office as desired from the PI. Current facilities exist, including environmental testing and clean rooms to support these efforts.

Program Cost Estimation

Using the benefits of the existing contractor support organizations and on-site civil servant engineering, the CubeSat program would be able to improve on the current amortized per mission costs of the existing programs. The WFF FY10 costs (not including payloads) are $47M for the sounding rockets, $26.7M for balloons, $3.2M for aircraft, and $19.1M for the range. Each of these suborbital programs is producing approximately 15 missions apiece. Included in these costs are the actual costs of the launch vehicles and the operational costs of the launch effort. By manifesting CubeSat missions on existing host missions, most of these costs are eliminated. CubeSat launch costs are assumed to be $50k/1U, with an additional $100k to handle launch vehicle related documentation, interface, integration, and deployer procurement and testing. Using the numbers above and assuming a program of 12 missions a year once up and running, the per mission program execution cost would be less than $1M.

Modeled after the sounding rocket and balloon programs, there will be a small Program office at WFF to manage the CubeSat Program. The CubeSat Program will work in cooperation with the

Title	Function	Yearly Cost ($K)
Program Manager	Manages overall CubeSat Program	200
Deputy Program Manager/ Technical Manager	Manages Principal Investigator interactions and integration and test support	200
Resource Analyst	Manages Program budget	100
Grants Manager	Supports NASA HQ managed solicitations and awards	100
Safety	Prepares risk analysis and mitigation plans	100
Engineering Support	Supports integration and test and technology development	200
Contract Funding	Electro-mechanical support, integration and test, engineering support, and institutional support	7000
Total		**7900**

existing sounding rocket and balloon programs, using existing contract arrangements and infrastructure. The table above summarizes the yearly program office costs.

The NSF CubeSat program invests ~$900k over three years per experiment, and we assume a similar baseline in this paper. Assuming four new CubeSat awards per year, the program could fund 12 experiments per year (four in their first year, four in their second year, and four in their third) at a yearly cost of $300k/year, plus an additional $250k/launch (four per year). The total yearly science payload cost is then $4.6M. Including the WFF support, the required NASA investment would be $12.5M/year, a relatively modest cost for such a high return-on-investment program.

Summary

With a relatively modest yearly investment of $12.5M NASA could expand the Suborbital and Special Orbital Projects Office to fund 12 simultaneous CubeSat investigations and four launches per year. The program could build upon the highly successful sounding rocket and balloon programs, and leverage existing resources for a high return on investment. We encourage the panel to examine other implementations of a NASA CubeSat program as well, such as partnering directly with the existing NSF program or implementing an NSF-style CubeSat program within NASA. Regardless of how a program is implemented, the benefits for rapid, focused science return, training the next generation of scientists and engineers, and advancing small technologies and instrumentation would be enormous, and are needed to maintain the NASA workforce. The addition of a CubeSat platform alongside the sounding rocket and balloon platforms enables a much larger range of science questions to be addressed, opening up a new area of space exploration to the next generation. Further, the NSF program has proven that the scientific opportunities enabled by CubeSats are in high demand, attracting proposers from the smallest universities to the largest labs. The CubeSat platform is also suited for Earth observing and small astrophysics missions, providing even greater breadth of science return and possible additional funding from other divisions. Finally, we note that each platform – sounding rockets, balloons and CubeSats – provide clearly differentiated science platforms, and including CubeSats in the SSOPD at the expense of funding the existing sounding rocket and balloon programs would be detrimental to the health and vibrancy of the community.

Magnetospheric Constellation

Tracing the flow of mass and energy from the solar wind through the magnetosphere

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1. Executive Summary

The Magnetospheric Constellation (MagCon) mission is designed to understand the transport of mass and energy across the boundaries of and within Earth's magnetosphere using a constellation of up to 36 small satellites. Energy is input into the geospace system at the dayside and flank magnetopause, yet we still do not understand the azimuthal extent of dayside reconnection sites, nor do we have a quantifiable understanding of how much energy enters the magnetosphere during different solar wind conditions. On the nightside, impulsive flows at various spatial and temporal scales occur frequently during storms and substorms and couple to the ionosphere through still unresolved physical mechanisms. A distributed array of small satellites is the required tool for unraveling the physics of magnetospheric mass and energy transport while providing definitive determinations of how major solar events lead to specific types of space weather. MagCon will map the global circulation of magnetic fields and plasma flows within a domain extending from just above the Earth's surface to ~22 Earth radii (RE) radius, at all local times, on spatial scales from 1-5 RE and minimum time scales of 3-10 seconds. It will reveal simultaneously for the first time both the global spatial structures and temporal evolution of the magnetotail, the dayside and flank magnetopause, and the nightside transition region, leading to the physical understanding of system dynamics and energy transport across all scales. It directly addresses LWS program goal #8, "Dynamic Geospace Coupling," while also providing the often required but currently missing global magnetospheric context for ionospheric, thermospheric and inner magnetospheric missions. The technologies required for MagCon are fully developed and flight validated owing to the success of the New Millennium Space Technology 5 (ST-5) Mission. MagCon is ready to be implemented today, with no further technology or instrument development.

2. Science Objectives

The MagCon science objective is to determine how the magnetosphere processes, stores, and releases energy derived from the solar wind-magnetosphere interaction. While these processes are fundamental for understanding the magnetosphere as a plasma laboratory, they are also fundamental for understanding and predicting the space weather of the near-Earth environment. Our lack of knowledge regarding the basic processes occurring within the magnetosphere and at the magnetospheric boundary is a major impediment for transitioning basic scientific knowledge of the geospace system into operational use, and hampers our ability to safeguard the human journey into space. MagCon represents a synergy between understanding of basic physical processes and real-world application of this knowledge for the protection of our technology-dependent society. MagCon seeks to understand the magnetospheric system as a whole, by studying not the individual pieces one-at-a-time, but through multipoint measurements across the entire system. With concomitant ground, low-altitude, solar, and solar wind measurements, MagCon would revolutionize our understanding of the magnetospheric response to dynamic solar wind input and the linkages across systems, and hearken in an era of systems science investigations.

The MagCon science objective can be broken into two over-arching focus areas: 1) mass and energy transfer into the magnetosphere occurring at the magnetospheric boundary; and 2) mass and energy storage, transport and release within the magnetosphere.

The magnetopause boundary, both at the dayside and flanks, is the site where solar wind flow energy is transferred into the magnetosphere. Magnetic reconnection is believed to be the dominant mechanism of energy transfer during southward IMF, yet we do not know the temporal or spatial scales of reconnection. Other coupling mechanisms, including the Kelvin–Helmholtz instability and diffusion induced by wave–particle interactions, provide additional mass and energy transport across the magnetopause boundary. In addition to fundamental questions regarding the interaction, we still do not have a quantitative understanding of energy transfer into the magnetosphere. The best coupling functions are able to account for only 70-80% of the observed energy input, suggesting major gaps in our understanding of the coupling. Substantial questions regarding the input and transfer of energy into the magnetosphere remain, and single point or narrow clusters of observations remain inadequate to the task of understanding when, where, and under what conditions the different modes of energy input occur. Only MagCon offers the ability to finally understand the critical pathways of energy input.

Meanwhile, the magnetotail is a critical volume of geospace for energy storage and releases, where global circulation of magnetic fields and plasmas is regulated in response to changing solar wind conditions. In it, impulsive, localized flow bursts launch and dissipate, powerful electrical currents form and evolve abruptly, and magnetic energy is explosively converted to particle energy. The scale, dynamism, and evolution of the magnetotail have evaded our efforts to observe and understand it using individual spacecraft. Fundamental questions concerning the dynamic response of the magnetotail remain unanswerable with the current observatories.

Magnetospheric Constellation is the logical outgrowth of a sequence of Explorer and STP missions designed to explore plasma transport and energy conversion processes over spatial sizes ranging from the distance to the Sun to the size of low energy particle gyro-orbits. The Magnetospheric Multiscale (MMS) mission will focus on the smallest scale, targeting the microphysical processes of magnetic reconnection. The THEMIS mission targeted a one-dimensional view of the magnetotail, a substantial advancement over the study of complex phenomena using individual spacecraft. Yet this one-dimensional mission was designed to answer a narrowly defined question of which of the two substorm models was acting. MagCon will establish a 2-D array of spacecraft both along and across the magnetopause boundary and the magnetotail, designed to produce for the first time a truly complete understanding of mass and energy transport. Ultimately, it will yield a new foundation on which we shall build a predictive science of next generation magnetospheric meteorology and forecast models, adding to our collective body of knowledge relating to fundamental physics of space weather behavior. It directly addresses LWS program goal #8, “Dynamic Geospace Coupling,” while also providing the often required but currently missing global magnetospheric context for ionospheric, thermospheric and inner magnetospheric missions.

2.1. Energy Input

The MagCon mission will provide observations critical to determining the relative importance and occurrence of different modes of energy transfer and transport during the solar wind–magnetosphere interaction at the dayside and flank magnetopause. A wide variety of models have been proposed to account for that interaction. Some models invoke steady processes such as reconnection along an extended neutral line or widespread diffusion induced by wave–particle interactions. Other models invoke transient local processes such as the Kelvin–Helmholtz instability or bursty reconnection driven by intrinsic magnetopause instabilities. Still other models invoke bursty merging or boundary waves triggered by the highly variable solar wind input, or the significant perturbations introduced into the solar wind by processes occurring within the foreshock.

It is likely that all mechanisms occur, but with a still unknown dependence on both solar wind conditions and the local plasma environment. The signatures of each of the proposed mechanisms are known both theoretically and observationally. Reconnection produces high-speed plasma flows on interconnected magnetosheath–magnetosphere magnetic field lines, whereas diffusion produces a low-latitude boundary layer on closed magnetic field lines, the dimensions of which grow with downstream distance. Bursty reconnection produces flux transfer events, or FTEs – bundles of interconnected magnetic field lines that bulge outward into both the magnetosheath and magnetosphere. The Kelvin-Helmholtz instability produces anti-Sunward-moving waves on the inner and outer edges of the low-latitude boundary layer. Pressure pulses in the solar wind drive waves that propagate dawnward or duskward across local noon in accordance with the spiral/orthospiral IMF orientation. The significance of each proposed mechanism depends on the amount of mass, momentum, and energy it transfers to the magnetosphere as a function of solar wind conditions. These parameters can, in turn, be estimated from the occurrence patterns and spatial dimensions of the phenomena generated by each mechanism. Single point measurements have been able to provide only glimpses into the importance of these various processes. To date, the lack of distributed simultaneous observations has precluded accurate estimates. Although Cluster and THEMIS observations have provided important details on the dynamics of individual, small-scale events, they do not have the instantaneous local time coverage necessary to determine the azimuthal extent of the interaction – a necessary observation for calculating the total energy input to the magnetosphere. Only the Constellation array of spacecraft will provide precisely the observations needed to make the estimates: simultaneous magnetopause, magnetosheath, and solar wind observations over a wide range of local times and solar wind conditions.

An example of how gaps in knowledge of dayside energy transfer inhibits understanding the magnetosphere as a system is the recent discovery that the polar cap potential saturates under certain solar wind conditions. One leading theory suggests a saturation of dayside reconnection, a process neither THEMIS nor Cluster has the capability of understanding. A saturation of dayside reconnection implies that there is a limit on the rate of energy that can be input into the magnetosphere, with obvious implications for magnetospheric energy transfer and near-Earth space weather effects.

The MagCon science objectives for energy input are (1) determine the instantaneous temporal and spatial (particularly longitudinal) extent of energy transfer phenomena; (2) Determine quantitatively the extent of magnetopause reconnection as functions of solar wind conditions; (3) Compare the total amount of input energy as a function of solar wind conditions and determine the dominant mechanism under a specific condition. In conjunction, these observations will provide a decisive answer to some of the most long-standing and controversial questions in magnetospheric physics, and enable a significant leap forward in our ability to model and predict space weather conditions.

2.2. Energy transport, storage and release

The magnetotail loading and unloading cycle of magnetic flux and energy plays a dominant role in magnetospheric activity, ionospheric energy deposition, and inner magnetospheric particle acceleration. The magnetosphere responds to energy input differently under various solar wind conditions, in ways that are not completely understood. For example, under extreme driving geomagnetic storms occur, leading to enhancements of the ring current and significant energy deposition into the atmosphere. Under less extreme but more common conditions, substorms, pseudo-breakups, and BBFs are members of a continuous distribution of impulsive, often localized magnetotail transport. Steady magnetospheric convection and sawtooth events represent intermediate modes of magnetospheric response that are poorly understood. All of these modes couple solar wind energy into the inner magnetosphere and the IT system, and our inability to fully characterize the responses leaves a critical gap in our ability to model and predict space weather impacts.

Mass and energy transport in the magnetotail involves spatial scales ranging from the azimuthal extent of localized fast flows, ~1–2 RE and possibly smaller, up to the largest scales that can be contained in the tail, as well as all temporal scales ranging from a few tens of seconds up to several hours, the typical substorm duration. To understand the flow of mass and energy through the magnetotail, the plasma sheet must be observed over all of these spatial scales simultaneously and continuously. Only a constellation of spacecraft that is distributed over the plasmasheet can accomplish this and provide global "images" of plasma convection, providing definitive, quantitative answers to the questions of how mass and energy flow through the geomagnetic tail.

The plasmasheet is also a region of plasma heating and acceleration, and is known to be a "seed" source of particles for the radiation belts and inner magnetosphere. There is great uncertainty concerning the true spatial, temporal, and energy distribution of the 20–500 keV "seed electrons" in the plasmasheet that are further energized via transport into stronger magnetic field regions. Transport of seed electrons occurs through a combination of processes such as earthward convection, radial diffusion and local acceleration by substorm injections during dipolarization events. An objective of the MagCon mission will be to sort out the relative importance of these various processes in determining the seed populations injected into the inner magnetosphere from the plasma sheet. This is an essential element in developing radiation belt models to predictive capability.

Results from the THEMIS and Cluster missions have highlighted the importance of the nightside transition region located between inner magnetospheric dipolar and stretched tail field lines. In this region flow bursts are braked and deflected, flux pile-up and dipolarization occurs, particles are rapidly energized and injected into the inner magnetosphere, and strong field-aligned currents couple the ionosphere to magnetospheric drivers. It is also a location of discrete auroral arcs, and despite their obvious importance in linking the magnetosphere to the ionosphere, we still do not understand the underlying magnetospheric drivers. A major impediment for determining these drivers is the inability to map ionospheric signatures to the magnetosphere. MagCon will provide the needed multipoint measurements required to finally determine the magnetospheric driver of auroral arcs.

A constellation array of spacecraft provides simultaneous observations of the plasmasheet and inner magnetosphere over a wide range of spatial scales. These observations will enable us to: (1) determine the spatial scales and temporal evolution of mass and energy transport during the different convection modes and in response to changing solar wind conditions; (2) reveal the coupling of the MI system at the transition region and determine the magnetospheric drivers of auroral arcs; and (3) determine the source and energization mechanisms of seed electrons. Thus, the fundamental nature of energy storage, transport and release in the magnetotail will be revealed by the distributed constellation of spacecraft that the MagCon mission will provide.

3. Technical Implementation

Enabling technologies for MagCon have been developed and flight validated for the ST–5 mission that was part of the New Millennium Program. Neither new technology nor instrument development is required. In the following sections we outline several implementations for achieving the MagCon science objectives.

3.1. Spacecraft Bus & instrumentation

The ST-5 spacecraft bus was developed at NASA GSFC as part of the New Millennium Program. It is a small (~25 kg), spin-stabilized spacecraft capable of science investigations from LEO out to beyond geosynchronous orbit. The bus has sufficient mass and power resources to support typical magnetospheric instrumentation such as electrostatic analyzers, solid-state detectors, electric field investigations, and magnetometers. The bus is simple, consisting of high TRL components.

	CBE	CBE w/ cont.	Power
Structure	9.49	10.04	0.00
Power	5.20	5.42	1.10
ACS	0.41	0.42	0.31
Propulsion	2.25	2.32	0.20
C&DH	2.30	2.88	5.00
Comm.	3.20	3.49	3.60
Thermal	0.77	0.81	0.70
Harness	2.97	3.51	0.03
Instrumentation	5.80	6.34	4.50
Totals	**32.39**	**35.22**	**15.44**

Table 1. CBE mass [kg] and power [W] for the MagCon spinners, including ESA, magnetometer and SST instrumentation. Peak communication power is estimated at 14.2 W. Available power is 24 W.

An updated ST-5 bus has been scoped for MagCon. Additional batteries are included for power during eclipses, and some additional shielding has been added for radiation tolerance. Four additional cold-gas microthrusters are included to assist with orbit, attitude and spin control. Pressurizing the original cold gas tank to full pressure increases the onboard delta-V capability for each probe to ~17 m/s, which we believe to be sufficient for the limited orbital maneuvers required for the mission. Cold-gas systems are ideal for a multi-spacecraft build of this type, since they are simple, safe, inexpensive, and do not require special handling, thereby keeping costs down.

To carry out the science investigations outlined in Section 2, the MagCon probes will require a magnetometer and electrostatic analyzer to achieve the minimum science objectives. The addition of a small solid-state telescope would add little cost but would enhance the science return greatly (particularly for an inner magnetosphere petal). ST-5 carried a miniature fluxgate magnetometer mounted atop a small boom. Neither the magnetometer nor the boom require any re-engineering for MagCon, and could be used as designed. The addition of both an electrostatic analyzer and solid state telescope of the size and mass of the THEMIS ESA and SST, for example, is easily accommodated. Table 1 summarizes the current best estimate (CBE) for mass and power usage for the MagCon bus. The low mass contingency for some subsystems is based on the high TRL level of the individual components.

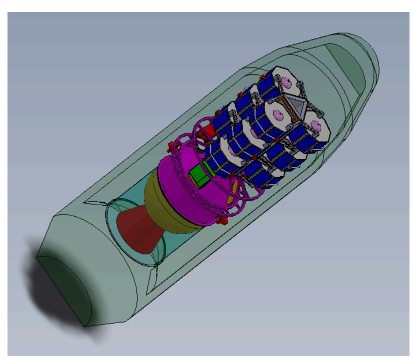

Figure 1. The nine MagCon deployer configuration.

3.2. Carrier

Figure 1 shows nine ST-5 spacecraft mounted atop a STAR37-FM kick motor, within a Taurus fairing. This represents the launch configuration needed for the inner MagCon petal, described below. Other launches would contain 12 spacecraft in a similar configuration, but contained within the larger fairing of a Falcon-9 or equivalent, and with a larger STAR-48B kick motor. The primary function of the carrier spacecraft is to orient itself for a perigee raise and ignite the kick motor. Coarse star trackers, gyros and cold gas propulsion should provide sufficient attitude control. It is not necessary for the carrier to reorient after perigee raise during deployment of the MagCon probes, as each spacecraft would contain sufficient delta-V resources to trim orbits as required. This reduces the complexity (and hence cost) of the carrier. Further information on the requirements levied on the carrier is provided below.

	CBE	CBE w/ cont.
Structure	124.6	141.1
Power	1.6	1.8
ACS	10.0	11.4
Propulsion	81.9	84.4
C&DH	2.5	2.9
Comm.	2.5	2.8
Thermal	1.6	1.6
Harness	5.0	6.3
Totals	**229.7**	**252.1**

Table 2. CBE mass [kg] for the 12 probe deployer.

The dry mass estimate of the 12-probe carrier is shown in Table 2. The mass numbers for propulsion include only the kick motor casing and associated mating structures, and does not include the mass of the cold gas system required for attitude changes, nor the kick motor propellant mass (which are included in Table 3).

3.3. Deployment

A notional deployment scheme is as follows. The Falcon-9 (or equivalent) launch vehicle delivers the carrier directly into an initial orbit with perigee near 150 km and the required science apogee. The carrier separates from the launch vehicle with little to no spin, and reorients using the cold gas propulsion system such that the kick motor burn at apogee will be nominally in the direction of motion. Prior to the kick motor burn the carrier spins up for stability and ignites the motor, raising perigee to ~7 RE. Note that there is no science requirement for precise apogee or perigee, greatly reducing requirements levied on the carrier spacecraft. Once the final science orbit is established following the kick motor burn, the individual MagCon spinners are deployed, with no specific orientation required. Each spacecraft carries sufficient onboard delta-V to reorient so that the spin axis is nominally perpendicular to the ecliptic, spin up or down as required, and impart delta-V as necessary to move ahead of or behind its neighbor, as necessary to achieve the required orbit separations.

The deployment and orbit insertion are designed to be as simple as possible, minimizing complexity, risk, and cost of the carrier while simultaneously meeting the science requirements of the mission.

3.4. Launch Vehicle

A past impediment to a missions requiring multiple launches was the prohibitively high-costs of available launch vehicles. The recent development of the SpaceX Falcon-9 and Orbital Sciences Taurus-II medium launchers makes a multiple launch mission feasible and a mission such as MagCon cost effective. Because the carrier spacecraft by design will not have the ability to perform a plane change, the initial orbit insertion will be directly into the desired orbit inclination, likely to be in the range of 9-12°. A launch from the Cape into this inclination incurs a significant mass penalty, but the baseline payload does

	Apogee			
	9 RE	**12 RE**	**16 RE**	**22 RE**
Total Probe Mass	315	420	420	420
Carrier Mass	215	250	250	250
Total Dry Mass	530	670	670	670
Wet Mass Required	760	1140	1200	1250
Launch Mass	1,290	1,810	1870	1,920
Cape lift margin (15°)	**N/A**	**33%**	**31%**	**15%**
Kwajalein lift margin (9°)	**9%**	**56%**	**54%**	**49%**

Table 3. Total mass rack-up for the different launch configurations, including lift margins. Orbit insertion is assumed to be 150 km x the listed apogee. Perigee raise is to 7 RE.

have sufficient lift margin. We included lift margins from Kwajalein for comparison.

3.5. Data collection & Communication

Data collection from a constellation of up to 36 spacecraft will require some degree of automation in order to keep Phase E costs reasonable. Decreasing the number of personnel required to manage 36 probes is essential for maintaining a cost-effective mission. In the latter half of the mission ST-5 successfully demonstrated a “lights-out” phase of mission operations, whereby the rapidly configurable architecture of the Goddard Mission Services Evolution Center (GMSEC) was allowed to operate the constellation and downlink data without intervention by ground personnel. The success of the ST-5 “lights-out” operations demonstrates a path forward for reducing cost and complexity for mission operations, and we suggest a similar mission operations and downlink paradigm for MagCon.

3.6. Mission Design

Achieving the stated science objectives of MagCon requires multiple spacecraft inside of ~22 RE with azimuthal separations of ~2 RE. To provide maximum flexibility we provide in Table 4 four examples of mission implementation, offering trade-offs between complexity, cost and science. The preferred option is MC33 that contains an inner petal passing through the inner magnetosphere. On the inbound and outbound legs of these elliptical orbits the 9 spacecraft would provide the inner magnetospheric field configuration, enabling for the first time an instantaneous snapshot of the magnetic field on the nightside magnetosphere. The benefits for obtaining such an accurate field state for relating ionospheric observations with magnetospheric drivers is enormous. The cost for this variant is slightly lower than MC36, due to 3 fewer spacecraft and launch on a Taurus rather than Falcon 9 (or equivalent), at the expense of a high radiation environment and likely slightly diminished lifetimes of those probes. One advantage of implementing MC36 or MC24 is that all spacecraft have perigees outside the radiation belt, thereby enabling a long lifetime for these probes, in stable orbits without de-orbit requirements, although the ability to fully characterize the magnetospheric magnetic configuration is diminished. All three launches would be identical as well, although we believe the non-recurring engineering (NRE) costs between the 9 and 12 spacecraft configurations is small. The remaining two options, MC24 and MC21, are designed to achieve the core objectives at lower cost, at the expense of magnetosheath and flank magnetopause science; it would also hamper efforts to capture magnetotail flows. MC21 offers a good balance between overall mission cost and science objectives.

Because of the onboard delta-V the probes could undergo several phases in which the azimuthal separation is adjusted. For example, Phase 1 could study azimuthal separations of 1-2 RE at the dayside magnetopause, the flanks, and plasmasheet. Phase 2 could extend these scale sizes to 2-5 RE, with wider

	MC36	MC33	MC24	MC21	Science objectives
9 @ 9 RE x 400 km		x		x	Inner mag field configuration; magnetospheric driver of auroral arcs; transition region
12 @ 10 x 7 RE	x		x		magnetospheric driver of auroral arcs; Transition region
12 @ 14 x 7 RE	x	x	x	x	Dayside magnetopause; azimuthal extent of flow bursts
12 @ 20 x 7 RE	x	x			Magnetosheath; flank magnetopause; azimuthal extent of flow bursts; flow burst origin and evolution
Cost[1]	$775M	$734M	$504M	$475M	

[1]Estimated phase B-D including 30% contingency and launch vehicle cost (Falcon 9 for 12 probe carriers, Taurus for 9 probe carrier)

Table 4. MagCon orbit configurations, science objectives enabled by each orbit, and estimated mission costs.

spatial coverage. Finally, the spacecraft could be placed equally along the orbits, providing global, instantaneous snapshots of the magnetosphere during an extended phase mission. Other variants include multiple clusters of satellites, for example 3 groups of 4 probes for the 12 probe configurations.

4. Program Cost Estimation & Schedule

We believe that due to the high TRLs of the spacecraft, carrier and instrumentation, combined with the successful validation of required technologies through the ST-5 program, MagCon can be costed to high fidelity. Based on extrapolation of a GSFC grassroots costing of a smaller constellation with the same instrumentation we have provided in Table 5 what we believe to be a realistic phase A-D funding profile for a 36-spacecraft MagCon design and build. Instrument costs are based on build-to-print instruments currently operating.

An important consideration is the extent to which the price of individual components can be reduced – each $100k cost reduction per spacecraft, for example saves $3.6M against the total budget. The avionics package and S-Band transceiver (~$1M/unit) in particular are two components that currently carry a high per-component cost. GSFC is currently working to reduce the recurring costs of these components, although we note that using currently available components the mission is already cost-viable.

	Phase A	Phase B	Phase C	Phase D1a	Phase D1b	Phase D1c	Phase D2	Phase B-D Dollars	Contin gency	Total B-D w/ contingency
	Pre Analysis	Definition	Design	Fab, Func. I&T	Obs. I&T	Prep for Launch	Launch & Checkout			
Phase Duration (months)	8.0	8.0	12.0	48.0	12.0	6.0	6.0			
1.0 Project Management	1.0	1.6	3.0	10.8	1.8	0.6	0.3	18.1	0.3	23.5
2.0 Systems Engineering	0.4	1.8	4.3	10.0	0.4	0.1	0.0	16.6	0.3	21.5
3.0 Safety & Mission Assurance	0.0	0.2	2.3	10.0	1.4	0.1	0.2	14.2	0.3	18.5
4.0 Science/Technology	1.00	3.00	3.00	5.75	0.25	0.00	0.00	12.0	0.3	15.6
5.0 Payload	0.1	1.5	3.0	36.0	3.0	0.3	2.0	45.8	0.3	59.5
6.0 Flight System										0.0
6.1 Carriers	0.8	5.6	12.0	120.0	9.5	3.3	0.9	151.3	0.3	196.7
6.2 Spinner #1	0.3	3.4	5.5	15.0	1.5	1.7	0.5	27.6	0.3	35.9
6.3 Spinner #2-N	0.0	0.0	0.0	99.1	54.0	8.0	3.6	164.7	0.3	214.1
7.0 Mission Ops	0.0	1.0	1.5	5.7	1.0	1.0	1.0	11.2	0.3	14.6
8.0 LVS										
9.0 Ground System	0.0	1.0	1.0	2.0	2.0	0.5	1.0	7.5	0.3	9.8
10.0 I&T	0.0	0.0	0.1	0.0	10.9	1.1	0.0	12.1	0.3	15.7
11.0 E/P O										
Totals	3.6	19.1	35.7	314.4	85.7	16.7	9.4	481.0		625.3
Launch Vehicles								150.0		150.0
Total cost	3.6	19.1	35.7	314.4	85.7	16.7	9.4	631.0		775.3

Table 5. Phase A-D cost estimates for MC36. Average recurring per spinner cost is $4.7M + $1.3M for payload. Average per carrier cost is $50M. Phase E costs are not estimated.

5. Summary

We have provided a set of mission options designed to determine how mass and energy flow through the boundaries of and within geospace. Magnetospheric constellations have been a long-acknowledged requirement for true understanding of the magnetosphere, appearing consistently in previous NASA Roadmaps. Yet to this point technical and cost concerns have postponed development of this mission. The fundamental science objectives of MagCon remain unsolved, and cannot be solved using single spacecraft or groups of tightly clustered spacecraft. With the success of ST-5, THEMIS, and other small satellite platforms, the technical and cost obstacles have been overcome. New, low-cost launch vehicles finally enable a multi-launch mission. The time for MagCon is now.

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Multi-Scale Investigations of Fundamental Physical Processes

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Science Target:
To understanding the role of coupling between different scales on particle acceleration, energy dissipation, and plasma transport in shocks, reconnection, and turbulence. This will be addressed by in situ measurements of particles and fields over a range of scales in the following regions: the solar wind and Earth's bow shock, the magnetopause, and the magnetotail.

Description
Understanding the fundamental physical processes that control the space environment has been identified as a priority goal by both NASA and the National Academy of Sciences. Through in situ data taken within the heliosphere, remote sensing of the solar surface and more distant astrophysical objects, and theoretical modeling, we know that the fundamental processes, shocks, reconnection and turbulence, play important roles in energy conversion and particle acceleration throughout the entire plasma universe. These processes are all inherently multi-scale, involving the coupling between electron, ion and fluid scales through the action of the self-consistent electromagnetic fields. Near-earth space provides an ideal laboratory for investigating these processes. The Earth's bow shock is a collisionless shock that responds to the changing input of the solar wind and interplanetary magnetic field, heating and accelerating charged particles. Reconnection occurs with different and varying boundary conditions, both at the dayside magnetopause and in the magnetotail. And turbulent processes occur throughout these regions, in the solar wind, the magnetosheath, in the boundaries and in the magnetotail. Studies of these regions with duel spacecraft (ISEE, AMPTE) [2] and multi-spacecraft missions (Cluster)[1] have shown that they are highly structure and spatially complex at every scale. The spacing(s) and time resolution available on these earlier missions allowed, for example, the bow shock and magnetic reconnection regions to be studied at the ion and fluid scales. The upcoming MMS mission [3] is designed to understand the microphysics of magnetic reconnection by determining the kinetic processes occurring in the electron diffusion region that are responsible for collisionless magnetic reconnection. The clear next step is to understand the cross-scale coupling in these regions by making simultaneous measurements over a range of scales. If one concentrates on only three key regions: the Earth's bow shock, the magnetopause, and the magnetotail one covers the most important physical processes in the entire universe: particle acceleration, magnetic reconnection, and turbulence.

- **Collisionless shocks**, such as the Earth bow shock, both heat the main plasma constituents and accelerate sub-populations of ions and electrons to high energies. This acceleration is possible because the physics involves more than one scale. Acceleration is therefore a part of the larger, complex, question about how shocks partition the bulk flow energy incident upon them, which again is distributed over fluid, ion, and electron scales. Variations in the driving flows, and instabilities within the transition scales, lead to transient phenomena that can significantly alter or enhance the acceleration efficiency. What mechanisms accelerate particles at shocks? How is the energy inflow on a shock partitioned between the various scales? How do shock variability and non-stationarity/reformation impact shock acceleration efficiency? How are electrons and heavy ions heated? Shock-shock interactions occur often in real systems, such as traveling interplanetary shocks colliding with planetary bow shocks, or forward shocks catching up with slower or reverse traveling shocks in strongly variable astrophysical systems. Theoretically, such interactions provide conditions for extreme heating and particle acceleration, and will be studied in detail for the first time by a cross-scale multi-spacecraft mission. MMS does not cross the bow shock during its prime mission, but it may in its extended phase. MMS is primarily focused on electron scales. This new mission will build on the knowledge gained from Cluster at the ion scales and MMS at the electron scales to address the inherently cross-scale physical processes.
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- **Magnetic reconnection** is expected to occur when magnetic fields are sheared across relatively thin current layers. In such current sheets the kinetic effects of the particle populations become important, and the onset of reconnection is expected to occur on the distance and time scales of the relevant electron and ion gyro-radius. Micro-scale processes control the change of topology of the magnetic field, eventually affecting the large-scale plasma mixing and converting magnetic energy to plasma energy. On the other hand, large-scale (MHD) processes control the location and formation of these thin current sheets, and thus directly affect how reconnection initiates and evolves. It is therefore essential to simultaneously follow both the large-scale and kinetic scale processes of the plasma to understand the onset, the evolution, and the result of magnetic reconnection. The dayside magnetopause and the magnetotail are prime locations to study reconnection. Questions that are still unanswered and can only be addressed by a cross-scale approach are: How does reconnection convert magnetic energy? How does the magnetic topology evolve and how are particles accelerated? What is the role of the various scales on these processes? As with shocks, this mission will build on the knowledge gained from MMS and Cluster to show how the large-scale topologies of reconnection affect the micro-scale processes and vice-versa.

- **Turbulence** is responsible for the transport of many physical quantities: energy, both between scales and across space; momentum; and energetic particles through the resulting complex, tangled magnetic fields. It covers a vast range of scales, from the very large MHD scale to below the electron gyro-radius. Significant advances in simulation, theory and observations have been made to understand the highly complex, non-linear and multi-scale nature of plasma turbulence. However, many important questions remain. For instance: how is energy transferred between scales, particularly at scales at which kinetic particle dynamics are important? What is the origin of the discrete structures that are observed in turbulent plasmas? These questions directly speak to how turbulence affects the surrounding plasma; without addressing them first, there is no hope to predict the large-scale effects and their spatial-temporal evolution in space plasma turbulence.

Therefore, the overall scientific objectives to be addressed are:

- To understand the role of coupling between different scales on energy dissipation, particle acceleration, and plasma transport in shocks, reconnection and turbulence.
-The specific science goals are the Cross-Scale-Coupling of plasma processes in the following key plasma regions: solar wind and Earth's bow shock, magnetopause, magneto-tail.

Observational variables:

-In order to address the questions of **shock heating and acceleration** in a way that can be applied universally requires a comprehensive characterization of the underlying plasma parameters on either side of the shock and within both the electron and ion scale. These include basic plasma moments (density, velocity, temperature, temperature anisotropies) for protons and heavy ions at cadences comparable to the relevant scales (< 2 sec. at the ion scale spacecraft, < 0.1s at the electron scale), and energetic particles. DC electric and magnetic fields at comparable, or slightly higher, cadences establish the global orientation and shock geometry, together with the basic sub-structure.

-For **reconnection investigations** the observations must be able to follow changes of current sheet (thickness, orientation, internal structures) that lead to reconnection. This requires timing analysis on current sheet features observed at the ion scale and to resolve any embedded electron-scale current layer, both with 4-point measurements at 5-50 km studying the electron scale and 100-500 km studying the ion scale. The corresponding cadence for these observations is ~0.01s for electron-scale observations and ~0.02s for ion-scale observations. In addition, a requirement for low-cadence (~1s) measurements on larger scales of the context for the reconnection process implies the need to measure plasma moments, composition, and energetic particles.

-To address key questions concerning the nature of **turbulence**, particularly near the ion and electron kinetic scales. Fields and particles will have to be measured simultaneously at the various physical scales. Ion and electron moments (density and velocity) and full 3D high resolution distribution functions of ions and 2D distribution functions of electrons are required from 3 spacecraft at ion/fluid scale and at least 2 spacecraft at electron scale. These should be at a temporal resolution of 0.1s for electrons and ~1s for ions. Similarly, AC and DC magnetic (3D) and electric (2D) fields measurements at 5-spacecraft for more than 1 scale required in the frequency range up to 200Hz.

Mission Concept and Implementation:

The primary requirement for a mission to measure the cross-scale coupling is simultaneous measurements over a range of scales. This requires at least 5 spacecraft, and ideally more. The spacecraft must go through the key regions – the bow shock, the magnetopause, and the tail reconnection regions. A 10x25-30 Re near-equatorial orbit would satisfy this constraint. In addition, the spacecraft must be well instrumented, with measurement cadences appropriate to the phenomenon that are being measured. Electrons at ~10 ms resolution, ions at ~200 ms resolution, plasma composition, energetic particle measurements with composition, and 3-component magnetic and electric fields must all be measured.

The comprehensive requirements for this multi-spacecraft mission make it expensive. For that reason, this mission is an ideal candidate for international cooperation. Missions addressing this science have been studied both in Japan and in Europe. The Japanese and Canadians have been studying a mission, called SCOPE [4], consisting of 5 spacecraft, two in close configuration (5-100 km) to address the electron scales and three more forming a tetrahedron to address the ion scales. The European scientific community investigated a larger scale version with 2 nested tetrahedra formed with 7 spacecraft covering the electron, and ion scales. This mission was proposed as a Class M mission to the Cosmic Vision AO, and was ultimately not selected. The community is now proposing a different implementation, called EidoSCOPE[5], that would provide an additional comprehensively instrumented spacecraft to SCOPE. The optimum mission might consist of three nested tetrahedral, using 12 spacecraft.

The NASA contribution could range from providing an instrument or multiple instruments to an international partner mission, providing additional instrumented spacecraft to be launched with a partner international mission to create a more complete configuration, or leading a complete mission to address these science goals. Here we describe the implementations based on SCOPE and Cross-Scale so that the cost of a US contribution at any level can be assessed.

Implementation:
SCOPE Implementation (being studied as a joint JAXA/CSA mission)

Orbit: 10x30 Re equatorial Orbit
Number of spacecraft: 5
Mother ship: Will contain a full set of instrumentation including

- 8 Fast electron ESAs
- 4 Fast Ion ESAs
- 1 Ion mass spectrometer (5 eV/q-25 keV/q)
- 1 Medium energy electron analyzer (2-100 keV)
- 1 Medium energy ion mass spectrometer (10-200 keV/q)
- 1 High energy electron instrument (30 keV-700 keV)
- 1 High energy Ion instrument (30 keV-1000 keV)
- Fluxgate magnetometer
- Search coil
- Electric field spin-plane wire antennas
- Electric field Spin axis antenna
- Wave-particle correlator

Near-Daughter(1)

Fluxgate Magnetometer
Electric field spin-plan wire antennas

Far Daughters (3)
2 Electron/Ion ESA's
Fluxgate Magnetometer
Search coil
Electric field spin-plane wire antennas
Electric field spin axis antenna

The mother ship, with a spin axis perpendicular to the orbital plane, will make the required high-time resolution electron measurements as well as the comprehensive measurements of the plasma composition and the accelerated energetic particles. The near-daughter will stay less than 10 km from the mother s/c, and will have a spin axis pointing towards the sun, so that it can make accurate measurements of the vertical DC electric field. The 3-component E and B wave fields will allow quantitative analysis of wave-particle interations on the electron scale. In the first phase, the far-daughters will stay < 100 km, and will also study the electron scale. In the second phase, they move to the ion scale to measure the true cross-scale phenomenon.

Formation:
The mother-far daughters will be close to a regular tetrahedron at apogee, while the near-daughter stays within 10 km of the mother ship. Timing must be synced between the spacecraft to within 0.1 msec.

Cross-scale Implementation (Proposed to ESA as a Class M Mission):

Orbit: 10x25 Re equatorial (14 degrees inclination) orbit.
Number of Spacecraft: 7
There will be one tetrahedron at the electron scale (spacecraft E1-E4), and one tetrahedron at the ion scale (spacecraft I1-I4), with one spacecraft serving as the corner for both tetrahedra.

Instrumentation:

	Number on Each Spacecraft				
Measurment	E1 and E2	E3	E4/I1 and I3	I2	I4
DC vector magnetic field	1	1	1	1	1
AC vector magnetic field	1	1	1	1	1
30-50 m wire double probe 2D electric field	8	1	8	8	8
3D electron ESA	4	0	2	2	2
Ion electrostatic analyzer	0	0	2	4	2
Ion composition analyzer	0	0	0	0	1
High energy particle detector	0	0	1	0	0

Cost:
Because of the large number of spacecraft and comprehensive instrumentation required for this mission, and the high interest shown by international partners in this science, this mission may be best achieved through partnership with others. Thus the cost can be tailored to what is required to make the overall mission achieve the science goals.

Relevance:
The first broad goal listed in the 2009 Heliophysics Roadmap is to "Understand the fundamental Physical Processes of the space environment." This mission addresses these key physical processes, focusing in particular on reconnection, Research Focus Area (RFA) F1, and on particle acceleration and transport, which is RFA F2. In fact Cross-scale/SCOPE is specifically mentioned as the next step on reconnection addressing "How do the large-scale topologies of magnetic reconnection affect microphysical processes, and vice-versa." Thus it directly supports NASA's goals. This science is also highlighted as a "science challenge" in the NRC Decadal Survey. The Decadal Survey lists as Challenge 4: "Understanding the basic physical principles manifest in processes observed in solar and space plasmas."

Summary:
Addressing the cross-scale nature of shocks, reconnection, and turbulence is the clear next step in understanding these fundamental physical processes in space plasmas. There is significant interest in the international community in launching a mission to address these topics. As these goals are also central to NASA's interests, NASA should leverage these opportunities, if possible, contributing instruments and/or spacecraft in order to enhance the overall scientific return from these missions. If the international opportunities do not materialize, these critical topics should be addressed with a stand-alone mission that would build on the achievements of MMS.

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The Importance of Ion Composition and Charge State Measurements for Magnetospheric Physics

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Only a small fraction of magnetospheric plasma instruments include ion composition measurements. For that reason, we know much more about the magnetospheric plasma in the aggregate sense than we do about its individual constituents and the roles they play in the global dynamics of the magnetosphere. Much of our understanding of that dynamics is therefore obscured by our relative uncertainty about how much O+ is present, for example, which is an important constituent because it is both common and relatively heavy. Because O+ is 16 times heavier than H+, microphysical processes like reconnection, plasma instabilities, wave generation, particle acceleration, pitch-angle scattering rates, and charge exchange interactions can show significant variation in their behaviors depending on the ion composition. Of course, other plasma constituents besides H+ and O+ also play a role in these physical processes. Some constituents (e.g. He++) can also be reliably inferred to be of solar origin rather than ionospheric, and can be used to track the sources of magnetospheric plasma in order to characterize and make progress toward understanding solar wind plasma entry into the magnetosphere and ionospheric outflow into the magnetosphere.

The Source of Magnetospheric Plasma

An area of continued debate is the source of magnetospheric plasma. While there are only two true candidates – the solar wind or the ionosphere – the research community would be hard pressed to come to an agreement as to which is of greatest importance. A further complication is the dominant entry mechanism, with plenty more hypotheses than potential plasma sources. This issue remains a large obstacle to our understanding of magnetospheric dynamics and is still a strong focus of researchers.

Early evidence for ionospheric sources came in the form of O+ measurements in these regions as presented by Shelley et al. [1974]. Confirming the first measurements were studies that found O+ composition increasing during increased solar and magnetospheric activity (e.g. Lennartsson and Shelley [1986]; Nosé et al. [2003]; Denton et al. [2005]). Others have taken a step further and concluded that ionospheric outflow is indeed the dominant source for plasma sheet and ring current plasma [Chappell et al., 1987]. Many of these studies assert that outflowing ionospheric plasma enters the plasma sheet as magnetic field lines convect (e.g. Chappell et al. [2000]). Solar wind sources remain a probable alternative, however. Measurements of the 33 boundary layers and plasma sheet [Eastman et al., 1985], especially detections of He++ [Lennartsson, 2001], imply plasma from solar wind origins. The entry mechanism is not yet agreed upon, with some presenting data and model work supporting entry through the dayside reconnection region [Lennartsson, 2001; Winglee, 2003; Moore et al., 2005], and others supporting flank entry [Eastman et al., 1985; Peroomian and El-Alaoui, 2008]. Very recently, Welling and Ridley [2010] demonstrated a two-mode source and entry system in MHD simulations that is dependent on solar wind conditions. For northward IMF Bz conditions, solar wind plasma entered through the flanks and dominated the inner magnetosphere. For southward IMF Bz, plasma from the ionosphere became the dominant source as it advected into the night side reconnection region then into the inner magnetosphere.

Unraveling this mystery requires measurements of plasma composition. Doubly ionized helium is an excellent indication of plasma from the solar wind. Conversely, an abundance of O+ is a clear signal that the ionosphere is playing an important role. The ability to clearly detect these different ions in the flanks, cusps, plasma sheet and inner magnetosphere will be required to establish their origin.

Composition Measurements and the Inner Magnetosphere.

It is now broadly accepted that the ionosphere becomes an import source of plasma during periods of active space weather. Singly ionized oxygen is an important constituent to this outflow, eventually contributing to the development of the storm time ring current. We know that the Numerous unanswered questions remain concerning outflow dynamics and the importance of ionospheric O+ to ring current development. How strongly does O+ contribute to the overall ring current? How does the delivery and concentration of O+ depend on solar wind conditions? Numerical simulations of the inner magnetosphere have worked to answer these questions, but without crucial measurements of plasma composition, it is impossible to connect numerical results to the observed magnetosphere.

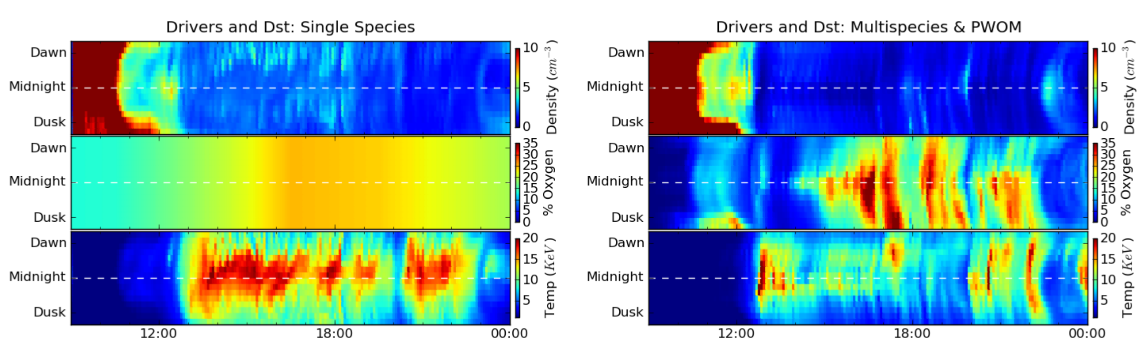

Figure 1: Comparison between number plasma density (top row), composition (percent O+ by count, center), and temperature (bottom) at

geosynchronous orbit as derived by single species MHD (left) and multi-species MHD with a polar wind outflow model (right). The vertical axis shows local time position such that the center of each plot is local midnight.

This problem is summarized by the results shown in Figure 1. Both show plasma conditions at geosynchronous orbit during the August 31st, 2005 moderate storm as derived by two different MHD models. On the left, single species MHD is combined with the Young et al. [1982] empirical relationship to provide H+ and O+ density and temperature. Because the empirical relationship is only dependent on the Kp index and solar F10.7 flux, it varies slowly with time and not at all with position. On the right, a numerical model of ionospheric outflow is used with multi-species MHD to create the same data set. Not only do temperature and density differ from the previous results, the percent O+ is now heavily dependent on time and position. When these inputs are used to drive an inner magnetosphere numerical model, the outputs are vastly different. But which yields results that are closer to reality? Without measurements of composition in the magnetosphere, we cannot be sure that the results gleaned from either set of inputs is a reasonable representation of the magnetosphere.

Composition and Waves

The composition of ion species in the magnetospheric plasma can also be very important in the generation, propagation, and effects of many types of wave emissions. These waves are of interest for several reasons. In some cases, they greatly affect magnetospheric dynamics because of their role in acceleration or losses of particles. But observations of the waves themselves can also be used as diagnostic tools for remotely measuring other parameters in the magnetosphere such as the plasma density. So, it is important to understand the wave emissions and the composition is a crucial part of the physics involved in most wave modes in the ULF and ELF ranges.

For example, electromagnetic ion cyclotron (EMIC) wave emissions are thought to play a large role in ring current and radiation belt dynamics. These waves below the proton cyclotron frequency are excited by anisotropies in the ring current ion distributions and they may cause losses of both ring current ions [Yuan et al., 2010] and radiation belt electrons [Ukhorsky et al., 2010]. The properties of the waves are heavily influenced by the relative ion composition averaged over all energies. This means that the most needed ion observations are at low energy (0.001-50 keV), since they dominate the average calculation. Studies of the wave emissions will often use average values of the composition because detailed ion measurements are not available.

Waves in the magnetosphere at even lower frequencies in the ULF range are also influenced by the ion composition. These emissions, also called ULF micropulsations, are excited by a variety of mechanisms, included pressure variations of the solar wind impacting the magnetopause, Kelvin-Helmholtz instabilities on the magnetopause flanks, and instabilities internal to the magnetosphere. Such pulsations have been shown to accelerate electrons up to radiation belt energies [Elkington, 2006]. Observations of these waves from the ground and in space may be used to investigate the global distribution of plasma in the magnetosphere [for example, Takahashi et al. 2006]. This technique is called "magnetoseismology" and it is similar to methods used to study the solar interior. Recently, Chi and Russell [2005] have used the propagation time of impulsive waves measured on the ground and in space to infer the global density distribution of magnetospheric plasma. The properties of the generation and propagation of these waves are controlled by the ion composition. Present models of the waves often use average or quiet-time values of the composition because of the paucity of measurements.

Conclusion

We are advocating for more ion composition instruments in the magnetosphere on future missions in order to resolve outstanding questions in magnetospheric physics. RBSP will include the HOPE instrument to characterize the ion composition of the low energy ring current, and there are a small number of current and past missions that included ion composition measurements. Nonetheless, ion composition is still one of the most sparse measurements in the magnetosphere, and is therefore one of the greatest sources of uncertainty as an input to magnetospheric models. These measurements will be critical for validating current magnetosphere models, and for data inputs if we are to transition current magnetosphere models to operational models.

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A Multi-Spacecraft Jupiter Space Plasma Explorer

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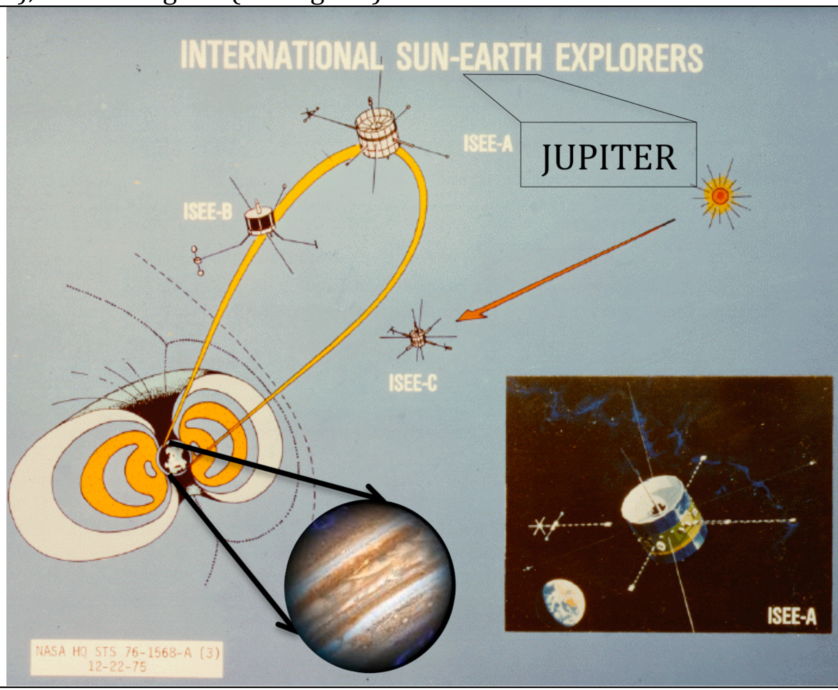

With multiple spacecraft orbiting Earth, the historic International Sun-Earth Explorers mission provided major leaps in our understanding of the solar wind-magnetosphere interactions. We propose a similar mission to Jupiter.

Abstract
We propose a multiple spacecraft mission to investigate the internally-driven Jovian magnetosphere and its interaction with the solar wind – to compare to Earth. Our proposal fits in the Panel on Solar Wind-Magnetosphere Interactions (SWM) and addresses two main points of scope of this decadal survey: (1) The characteristics and physics of the interplanetary medium from the surface of the Sun to interstellar space beyond the boundary of the heliosphere; and (2) The consequences of solar variability on the atmospheres and surfaces of other bodies in solar system, and the physics associated with the magnetospheres, ionospheres, thermospheres, mesospheres, and upper atmospheres of the Earth and other solar system bodies.

1 Background: Why Jupiter? Why Multiple Spacecraft?
Jupiter's magnetosphere (Figure 1) is the most powerful in the solar system – Jupiter's magnetic dipole moment is 20,000 times that of Earth's and its surface field is 14 times stronger. Jupiter's magnetosphere is strongly affected by Jupiter's 10-hour spin period and its internal plasma source: the moon Io. Volcanic activity at Io supplies ~1 ton/s of plasma to the magnetosphere, forming a plasma torus around the planet that emits terawatts of UV emission. This becomes a vast, rotating plasma sheet with associated currents and fields.

Past space missions provided foundational understanding of Jupiter's magnetosphere and future planetary missions (e.g. Juno, Europa Orbiter) will move our knowledge forward still. However, outstanding questions remain that only a space mission devoted to the jovispace plasma environment with simultaneous measurements from multiple spacecraft can answer: What drives large-scale magnetospheric flows? What is the nature of nightside reconnection and loss of iogenic material down the magnetotail? How does the solar wind (SW) interact with the dayside magnetopause and boundaries on the flanks?

"Typical of the rigor of physics is the need to change the parameters governing the system studied in order to test whether behavior varies as predicted."
M. Kivelson, *Learning about Earth's plasma processes from studies of other magnetospheres,* GEM, Snowmass, CO, 2010

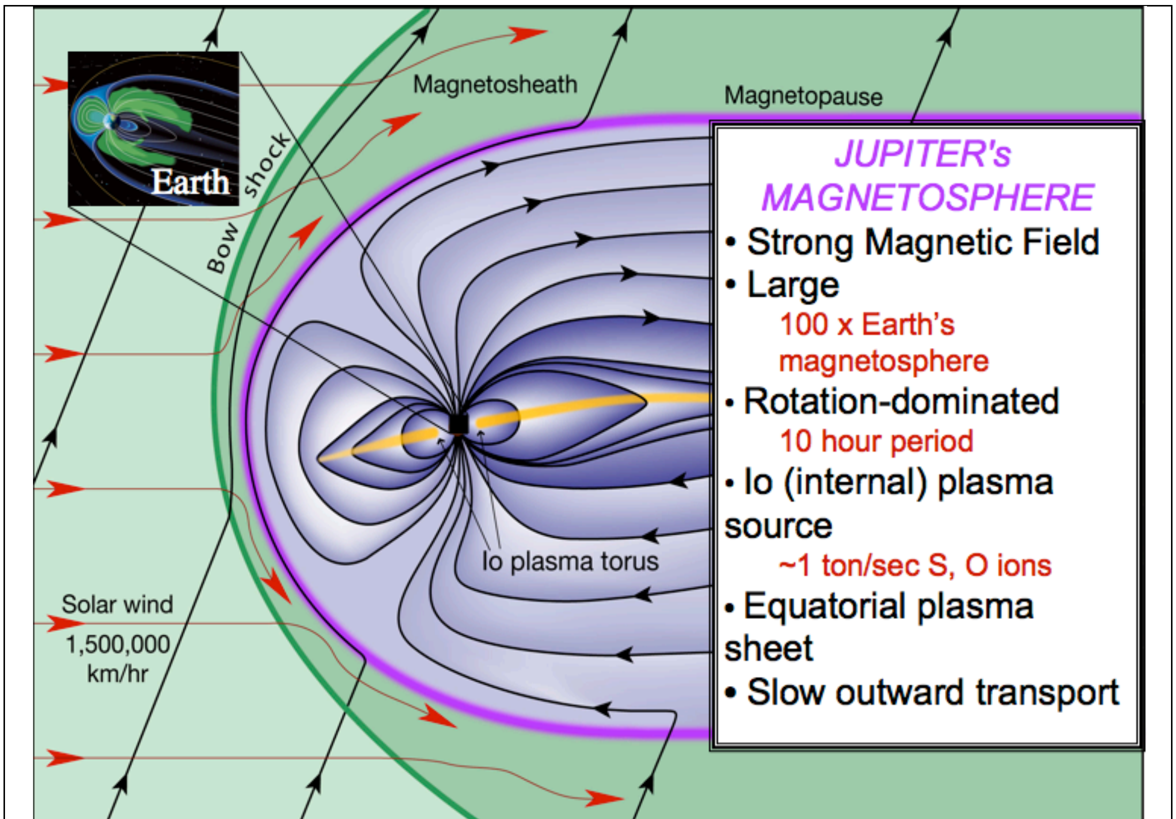

Fig. 1. **Jupiter's magnetosphere is vast, rotation dominated, with internal sources.**

Our understanding of the terrestrial magnetosphere and space plasma and interaction with the SW increased dramatically when we advanced to multiple spacecraft missions capable of breaking the space-time ambiguity of single point measurements of moving thin boundaries. The breakthrough mission was the International Sun-Earth Explorer Mission (ISEE).

ISEE-1 and ISEE-2 were in the same highly eccentric geocentric orbit with an apogee of 23 Earth radii and a small separation distance between them. They made simultaneous coordinated measurements to permit separation of spatial from temporal variations in the near-Earth SW, the bow shock, and inside the magnetosphere. ISEE-3 was in heliocentric orbit at L1 where it monitored changes in the near-Earth interplanetary medium. The three spacecraft carried a number of instruments for measuring plasmas, energetic particles, waves, and fields and was considered a tool for extending the investigations of solar and geomagnetic phenomena of previous spacecraft by enabling measurements from different points in time and space. The scientific goals were to investigate solar-terrestrial relationships at the outermost boundaries of Earth's magnetosphere, to examine in detail the structure of the SW near the Earth and the shock wave that forms the interface between the SW and the Earth's magnetosphere, and to investigate motions of and mechanisms operating in the plasma sheets. The Cluster and THEMIS missions have expanded in complexity and in science capability since the time of ISEE.

The ISEE mission greatly moved forward our understanding of the SW-magnetosphere interactions and its discoveries were dependent upon the multiple spacecraft configuration with the upstream SW monitor. Among other achievements, ISEE:

- Revealed plasma jets and magnetic flux ropes associated with magnetic reconnection at the magnetopause
- Observed vortical flows within the plasma sheet along the magnetotail flanks
- Discovered bursty bulk flow events in the magnetotail associated with reconnection in the magnetotail
- Revealed magnetosheath plasma flows along the flanks of the magnetosphere that were faster than that of the upstream wind with northward IMF
- Discovered offsets between the electron and ion edges of both the low latitude magnetopause boundary layer and the plasma sheet boundary layer owing to time of flight effects following reconnection
- Showed hemispherically symmetric (as opposed to the usual hemispherically asymmetric) polar rain results when closed field lines within CMEs in the SW reconnect with Earth's magnetic field at the dayside magnetopause, providing evidence that polar rain results from entry of the SW electron heat flux into the magnetosphere on open field lines

We consider the ISEE mission as a key precedent. The multi-craft design allows for measuring the space plasma environment in several key locations simultaneously – within and without the magnetosphere; in the plasma disc and in the boundary regions; in the dawn and dusk flank – all while monitoring the SW and the auroral energy output.

2 Scientific Objectives: What's Similar vs. Different from Earth?

We propose a $1B-class, multiple-spacecraft Jupiter explorer mission, building on the experience of such missions at Earth and on the legacy of previous missions to Jupiter. This mission will investigate the Jovian magnetospheric dynamics that result from plasma/magnetic field interactions and space plasma processes (e.g. reconnection, Kelvin-Helmholtz instabilities, and wave-particle interactions) by exploring:

- Dynamics of and mechanisms operating in the equatorial plasma disc surrounding Jupiter that lead to the high plasma β conditions found in the outer magnetosphere
- SW-magnetosphere relationships at boundary regions
- Dayside opening reconnection – steady state flux-transfer-events, effects of high β plasma, dependence on IMF
- Nightside closing reconnection – SW-driven (Dungey) versus centrifugally-driven (Vasyliunas)
- Kelvin-Helmholtz instabilities and the relative importance of viscous mixing processes (i.e. mass, momentum and energy input from the SW) at the magnetopause boundary

A prevailing idea has been that Jupiter's magnetosphere is essentially open, that magnetic reconnection with the IMF drives magnetospheric flows via a Dungey cycle of plasma circulation (similar to the terrestrial magnetosphere) and that the polar aurora is largely associated with magnetic flux open to the SW. A competing explanation is that magnetospheric flows are driven by viscous processes between SW and magnetospheric plasmas at the magnetopause boundary.

In general, the most important mesoscale processes that operate at magnetospheric boundaries are magnetic reconnection and Kelvin-Helmholtz modes. At Earth it is clear that magnetic reconnection and the associated Dungey cycle play a crucial role in the SW-magnetosphere interaction. However, it has been suggested that magnetic reconnection at Jupiter may not be important because: a) magnetic energy conversion is insufficient to affect corotational magnetospheric flows, and b) viscous processes (Kelvin-Helmholtz) are the dominant physical processes operating in Jupiter's high-β plasma environment .

	Msphere source	Dipole (x Earth)	SW dynamic pressure	Mpause standoff distance (dipole)	Mpause standoff distance (actual)	Plasma β (dayside msphere)	Alfvén speed ratio (msphere/ msheath)
Earth	H^+, O^+ ~5 kg/s	1	0.2-0.4 nPa	10 R_E	8-12 R_E	<1	5-10
Jupiter	S^{++}, O^+, H^+ ~1 ton/s	20,000	0.05-0.5 nPa	42 R_J	60-100 R_J	5-100	~1

Why send a mission to study at Jupiter what has already been studied at Earth? Both systems are embedded in the SW but at Jupiter (5 AU), the SW differs significantly from that near Earth, as seen in Table 1. Another key difference is that the dynamics that are internally driven by Jupiter's rapid rotation and the Iogenic plasma are of great importance. **The magnetospheres of Earth and Jupiter share similar underlying plasma physics; what causes the dramatic differences in scale and behavior?**

Fig. 2 shows how our mission concept measures important magnetospheric boundaries.

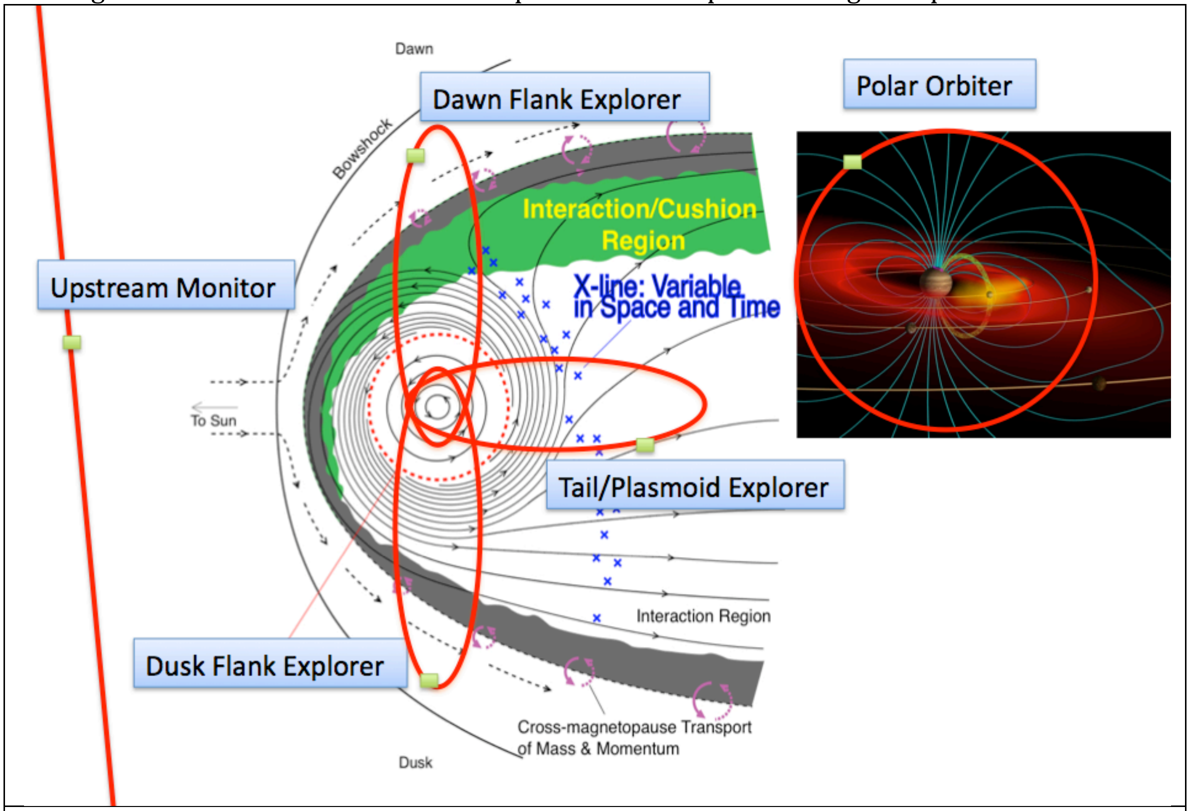

Fig. 2. Mission components: Upstream monitor in heliocentric orbit, Flank/Plasmoid explorers precess through local time over ~6 years, polar monitor in circular orbit.

Due to the rapid planetary rotation (10 hours) considerable dawn/dusk asymmetries are present in the system. A key aspect of this concept mission is to probe differences between the SW interaction on the dawn and dusk flanks. For example, Is plasma ejected at different rates, scales and/or mechanisms across the tail? Does Kelvin-Helmholtz operate on the dusk flank where shear flows are reduced? Does opening reconnection (Dungey) exhibit local time asymmetry? To address these issues it is key to sample all local times.

3 Spacecraft, Instrumentation, and Measurements

3.1 Component craft

Upstream Monitor

- Heliocentric orbit
- Magnetometer; Energetic particle detector; Plasma (ion+electron) instrument; Radio antenna + simple UV camera to monitor total Jovian auroral emissions.

The Upstream Monitor provides continuous monitoring of the SW and the auroral flux from Jupiter. Magnetometer will continuously monitor the IMF versus time and the plasma and energetic particle instruments will monitor the SW. The simple UV camera will measure the total auroral flux from Jupiter versus time. This provides the input power from the magnetosphere and the energy of the precipitating electrons. A radio antenna detects the strong jovian radio emissions. The spacecraft will be placed on a simple heliospheric orbit and timed so that aphelion is upstream of Jupiter, illustrated in Figure 3.

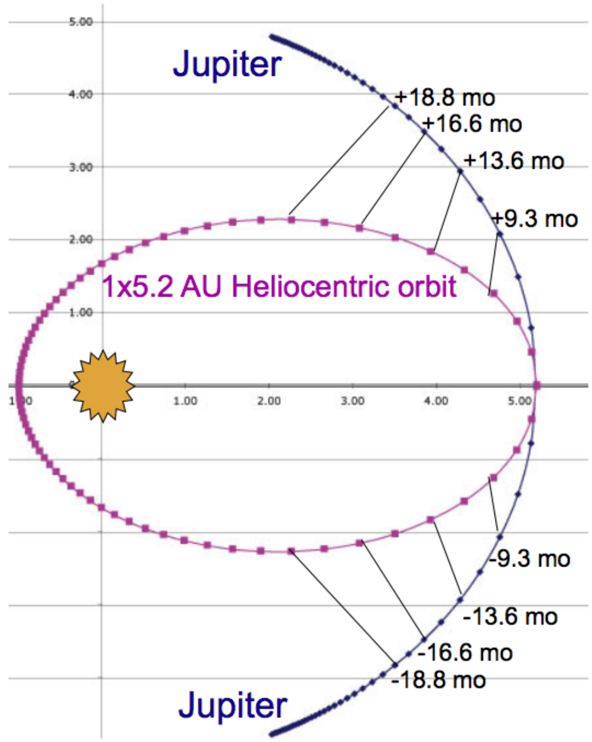

Fig.3: Concept orbit for the upstream solar wind monitor (3.1 AU semi-major axis). Note that the spacecraft spends 2 years within 1 AU of Jupiter.

This spacecraft essentially will make SW measurements that the U.S. space program made in the 1960s, but updated for the Jovispace environment with modern materials and electronics. This will be a low-cost mission component – low propulsion, power and data rate, on-board data processing – that would be appropriate for a partner space program to build and operate, e.g. Europe, Canada, Japan, India, China, or a nascent space-faring country. Alternatively, such a spacecraft could be designed, built and operated by a US university or educational consortium – such as LASP's SNOE spacecraft that orbited the Earth.

Another option for upstream monitoring is a probe in a highly eccentric Jovicentric orbit spending most of its time outside the magnetosphere. This would provide SW coverage until it precesses into the far down-tail region; then it would function as a far-tail probe. These options should be evaluated for feasibility and cost.

Jovian Magnetospheric Flank/Plasmoid Explorer

- Jovicentric, highly elliptical orbit
- Spinning spacecraft
- Magnetometer measures the magnitude and direction of the Jovispace magnetic field; Electric field instrument measures the magnitude and direction of the Jovispace electric field; Plasma instrument measures electrons and ions; Energetic particle detector measures energy and angular disctribution of energetic particles

The flank/plasmoid explorers will probe the magnetospheric environment in the active boundary regions by measuring the characteristics of both the plasma and magnetic fields. Perijove will be restricted to >15 R_J to keep the craft out of high radiation regions. In order to fully pass through the boundary regions, we suggest an apojove of ~100 R_J (which would keep the orbital period <30 days, raising the apojove to 200 R_J increases the orbital period to >120 days). These orbits will precess as Jupiter orbits the Sun (period ~12 years) allowing the flanks of the magnetopause boundaries at both dawn and dusk to be monitored as well as regions tailward of the magnetic x-line to monitor the release of plasmoids down the tail. These spacecraft will also measure the centifugally-confined plasma sheet that ultimately plays a central role in the SW/magnetosphere interaction. The orbit size and period should be optimized to achieve the science objectives with minimum propulsion mass, though some orbit adjustments may be feasible through flybys of Ganymede (~15 R_J).

Polar Orbiter

- Jovicentric, circular orbit
- Spinning spacecraft or nadir pointing (if UV monitor included)
- Magnetometer; Particles and fields experiments; UV monitor (optional)

In this mission, the polar orbiter measures the plasma and field environment in the polar region while the flank explorer and upstream monitors make measurements. An optional UV instrument could monitor the aurora. We propose a choice of two possible orbits: at 15 R_J (~7 day orbital period) the radiation exposure will be minimal and the orbit might be designed cross Ganymede's orbit at the equator, perhaps synchronized with Ganymede. In a circular 6 R_J orbit (1.75 day orbital period) the spacecraft faces greater radiation dosage, but the added science benefit is that it will pass through the Io plasma torus during each orbit. Although Juno will reveal a great deal about the plasma environment in the polar regions, the terrestrial experience with Dynamics Explorer and Polar missions have demonstrated the value of measuring the polar environment simultaneously with magnetospheric measurements.

3.2 Mission combination options

The selection of combinations of craft determines the scientific objectives. For any mission configuration the Upstream Monitor is essential. Without it, processes measured by other spacecraft cannot be linked with SW processes. We offer the following combinations of spacecraft in order of increasing complexity. In each case, the spacecraft precession over 6 years (Jupiter's orbital period is 12 years) will enable coverage of all local time.

- **Upstream + Single Flank/Plasmoid + Polar**

This configuration will make measurements of the magnetospheric environment in the dawn flank sector while simultaneously observing the polar environment.

- **Upstream + One Flank + One tail (Plasmoid) + Polar**

This configuration is designed to probe the differences between the dawn and dusk flanks of the magnetosphere while providing measurement of plasmoid release down the tail. In this configuration it may not be possible to simulateously monitor differences between the dawn and dusk flanks.

- **Upstream + Two Flank + One tail (Plasmoid) + Polar**

This configuration will provide simultaneous dawn and dusk measurements along with tail measurements to provide the most comprehensive local time monitoring of the system.

- **Upstream + Single Flank/Dual SC + (Polar option)**

In this configuration, the Flank Explorer is a mother/daughter dual spacecraft following the ISEE model. The mother and daughter craft, sharing the same orbit and maintaining a small separation distance, make simultaneous coordinated measurements in order to separate spatial from temporal variations. A cost-minimizing option could be for the daughter spacecraft to be minimally equipped, e.g. with only a magnetometer to monitor boundary crossings.

3.3 Auroral Support Observations

Ground-based telescopes and space telescopes will be used for auroral monitoring. The ionospheric response to magnetospheric inputs can be monitored with spatially-resolved high-resolution spectroscopy to measure temperature/density profiles in the auroral ionosphere and magnetospherically-driven ion flows. Monitoring auroral morphology is best achieved with UV imaging from a space telescope if that capability becomes available. Ground-based monitoring of Jupiter's strong radio emissions will also play an important role.

4 Cost

We make an initial estimate of a multi-mission to Jupiter based on participation of a foreign partner space agency for the Upstream Monitor. The Juno mission is a New Frontiers mission of NASA's Planetary Science Division that is of the order of ~$1B. The spacecraft proposed herein will be solar powered, using a system similar to the Juno spacecraft's high efficiency system, avoiding the cost of plutonium-238-fueled radioisotope power systems. Since the proposed multi-spacecraft orbits would not need to take data at the extremely rapid rates required by Juno (which skims the equatorial cloud deck and passes pole-to-pole in 2 hours) the power demand and size of solar panels would be reduced. Getting into orbits with perijoves of 15 Rj (or even 6 Rj) will require significantly less fuel than Juno's tight polar orbits. Similarly, if we keep the component spacecraft of a multi-spacecraft mission no closer than 15 R_J from Jupiter, avoiding the planet's radiation belts, we eliminate the need for the heavy radiation shielding (e.g. Juno's electronics vault). Thus, we estimate that NASA's Heliophysics Division could deliver 2 space physics spacecraft to Jupiter for a similar ~$1B price as Juno.

The time is ripe for a multiple-spacecraft-mission to address the puzzles of magnetospheric processes at Jupiter – in the way missions like ISEE gave us a clearer picture of the workings of Earth's magnetosphere.

A science mission concept to actively probe magnetosphere-ionosphere coupling

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Unlimited Release: LA-UR 10-07644

Description: This mission concept describes how directly mapping magnetic field lines from a magnetospheric satellite to their ionospheric footpoints using an on-board electron emitter and ground imaging techniques can answer long-standing fundamental questions of magnetosphere-ionosphere coupling

Introduction

This white paper is submitted to the *Panel on Atmosphere-Ionosphere-Magnetosphere Interactions (AIM)* for the Heliophysics Decadal Survey. We summarize a mission concept aimed at unambiguously relating ionospheric signatures to the causative magnetospheric conditions and magnetospheric regions and boundaries to their ionospheric signatures. This has been an open question since in situ observations first began to reveal the physical processes more than 50 years ago. Active experiments have shown promise throughout the years for resolving field line mapping ambiguities. In order to truly understand magnetosphere – ionosphere coupling we need to go beyond present limited methodologies that generally relate low altitude phenomena to high altitude phenomena through similarity or empirical models. The format of this paper is to first expand upon the scientific problem and then outline a potential feasible solution.

Next year, scientists will convene in Fairbanks, Alaska, for an AGU Chapman Conference on the Relationship Between Auroral Phenomenology and Magnetospheric Processes. From the conference description: "Some of the most interesting and pressing questions in space physics relate to the origin of auroral structure and dynamics, and the nature of acceleration and pitch angle scattering in the case of discrete and diffuse aurora, respectively. … The conference will provide an opportunity to present the latest results from analyses of experimental data (including space-borne, ground-based and co-ordinated data), simulation and theory, addressing various aspects of the aurora, in order to connect our knowledge of auroral morphology and mechanisms to candidate physical processes in the magnetosphere capable of powering and structuring the aurora on Earth and other planets." The topics to be addressed by this conference include the relationship between auroral and magnetospheric dynamics, fields, and gradients. In other words, one goal is to try to determine what it is in the magnetosphere that causes aurorae. Recently, the THEMIS mission has addressed global substorm processes through coordinated multi-point ground and in situ observations in a two dimensional plane [Angelopoulos, 2008]. However, lack of knowledge of field line mapping in the transition region between dipolar and highly stretched field lines leads to major unknowns in understanding the linkages between auroral ionospheric and magnetospheric processes.

The fact that these questions are still under active research and debate is testimony to the major challenge of trying to relate phenomena observed in the Earth's ionosphere with phenomena occurring tens of thousands of km away in space. The fundamental difficulty in attributing magnetospheric causality to auroral phenomena is (and always has been) the lack of definitive knowledge of the mapping between one and the other. In magnetospheric and ionospheric physics, the magnetic field is the conduit for the transmission of particle and electrodynamic communication. Therefore, while we have many ground and space observations of aurora and many in situ observations of magnetospheric properties and dynamics, relating them to each other requires knowing the magnetic connectivity between them. The challenge here is that the global magnetic field is strongly affected by currents flowing within the magnetosphere itself and is highly dynamic. This is particularly true in the region of space that is the probable source of most auroral phenomena.

Over the years considerable progress has been made in understanding the global structure of the magnetospheric magnetic field and its variability. Global MHD simulations [e.g., Raeder et al., 2001] demonstrate the strong distortions from the underlying dipolar geometry and how those distortions change based on the properties of the upstream solar wind. Since the early '80s, a class of empirical global field models derived from analysis of large quantities of in situ magnetic field measurements [e.g., Tsyganenko and Usmanov, 1982; Tsyganenko, 1989; Tsyganenko and Sitnov, 2007] has provided a quantitative description of the average global field topology under various conditions. These empirical models, parameterized by various relevant physical quantities such as solar-wind properties, show dramatic variations in the mappings from a given point in the magnetosphere to the ionosphere.

The empirical models have for the last decade served as the primary tool for relating ground- and space-based observations. However, efforts to compare the modeled field with various observations have revealed not only systematic differences [e.g., Fairfield, 1991; Donovan et al., 1992; Jordan et al., 1992; Peredo et al., 1993; Pulkkinen and Tsyganenko, 1996; Thomsen et al., 1996], but strikingly wide variability in magnetic field measurements for an individual event. A glance at the studies mentioned above demonstrates that the instantaneous variation from the model (or the statistical average) field vector is typically a substantial fraction of the average. Thus, as noted in the 2003 Decadal Survey for solar and space physics [NRC, 2003], "the actual instantaneous configuration of the magnetosphere is not expected ever to resemble any of its average states." Indeed, at any given time the magnetic field measured in situ can deviate significantly from that predicted by these various models. Thus, the mapping from ground to space may also be significantly different from the model expectations. For instance, THEMIS investigators report uncertainties in mapping auroral arcs at onset to be larger than 10 Earth radii [Substorm Expansion Focus Group Report, GEM conference, 2010].

These difficulties with using global empirical models to map between the magnetosphere and the auroral ionosphere have led numerous researchers to develop a range of techniques to try to determine the connectivity observationally. Using precipitating charged particle measurements made at low altitudes by polar-orbiting DMSP satellites, and noting the spectral similarities with particle distributions observed previously in various high-altitude regions of the magnetosphere, Newell and Meng and colleagues have mapped extensively the statistical ionospheric occurrence pattern of different regions of the magnetosphere [e.g., Newell and Meng, 1988, 1992, 1994].

Other authors have used low-altitude particle signatures to identify the magnetospheric source location for ionospheric phenomena such as traveling convection vortices (TCVs) [Moretto and Yahnin, 1998] and discrete aurorae [Yahnin et al., 1997] and to monitor the tail current sheet structure [Sergeev, 1995; Sergeev and Gvozdevsky, 1995; Sergeev and Kubyshkina, 1996]. Still other studies [e.g., Weiss et al., 1996] have compared low-altitude and high-altitude electron distributions during nominal conjunctions to identify times of best match, presumably when the satellites were on roughly the same field line. Recently, using THEMIS observations, Nishimura and collaborators have shown that individual chorus elements can be mapped to specific patches of pulsating aurora by comparing wave intensity to auroral luminosity [Nishimura et al., 2010]. The precision of this technique is very promising but its application to one specific phenomenology may limit its utility to global mapping issues.

Such studies have helped greatly to illuminate the regional connectivity between the ionosphere and the magnetosphere and have provided the crucial link enabling the global association between certain ionospheric conditions and the conjugate magnetospheric region. However, such regional mappings are generally unable to specify the location and conditions within a given magnetospheric region that is magnetically connected to the ionospheric footpoint. Even in the case of boundary crossings, where the mapping is well localized in one dimension (normal to the boundary), there is great uncertainty about the exact mapping along the boundary. Hence, it is only by rough inference that specific magnetospheric features can be related to specific ionospheric features through their proximity to various regional boundaries.

The ability to definitively identify the magnetic field mapping from over large distances stands in the way of a full, unambiguous understanding of which conditions in the magnetosphere give rise to various ionospheric signatures. One remedy is to use charged particles as field-line tracers, emitting them in one region and detecting them in the other. Combined with appropriate local diagnostics of ionospheric signatures and magnetospheric conditions, such a capability would enable us to definitively connect the physics and the signatures, which is the real prerequisite for magnetosphere-ionosphere coupling studies. Insight gained from this definitive mapping has the potential to "enlighten a space age of measurements" enabling past and future measurements to be placed into the correct context between the ionosphere and the magnetosphere. The mapping allows determination of who drives who, and a vastly improved understanding of the linking between these two regions.

Mission Concept

One feasible technique for determining the magnetic connectivity would be to fly an electron beam generator on a magnetospheric satellite, which would periodically emit an intense beam of electrons parallel to the magnetic field. Such electrons would follow the field down to the ionosphere, where they could be detected via their optical or radar signature. Combining local magnetospheric diagnostics on and near the spacecraft with auroral and convective signatures at the ionospheric location of the beam spot would produce an unambiguous linkage between the ionospheric signatures and the causative conditions in the magnetospheric source region.

This mission is envisioned to include an active electron injector in space, with a plasma contactor to neutralize the payload and permit ambient measurements immediately before and after the injected electron beam pulsing. In situ observations of plasma and electric and magnetic waves are considered critical. Also critical are electron drift measurements and those of ion composition; both missing on THEMIS. The orbit can be highly elliptical with apogee chosen to allow optimal long conjunctions over the ground detection sites. Though this mapping technique is broadly applicable for numerous regions, the highest priority orbit would explore the dynamic under-sampled transition region field lines in the nightside magnetotail approximately 1-3 Earth radii beyond geosynchronous orbit.

The highest risk items for this mission are the present paucity of space flight qualified electron injectors and the uncertainty of seeing the electron beam spot. The former risk can be addressed head-on; the best strategy is to merge the expertise of groups building compact electron accelerators for terrestrial vacuum applications with those of high power space engineering applications. The latter risk can be reduced through modeling efforts, injector optimization, and redundant beam detection efforts. Both optical and radar based detection can resolve a beam of reasonable power with a sufficient signal to noise ratio. Recent technological advances in numerous relevant areas (camera sensitivity and noise, radar arrays, plasma contactors, and electron injectors) enable a highly feasible mission with lower resources.

Relatively modest spacecraft and instrumentation with high heritage make this a relatively low-cost mission, perhaps even within the Explorer program budget cap. If larger programs and launch vehicles are available, other mission configurations (e.g. multiple vehicle missions) may become viable. A complete cost benefit analysis of the additional science to be gained by multiple in situ spacecraft has not been performed.

This technique can be applied to key questions in other areas of the magnetosphere. Numerous other complementary efforts are identified, e.g. ground-based and suborbital campaigns. The THEMIS mission has placed greater urgency upon these questions. Active experiments have a rich history of important contributions to the field of space physics and are the only direct ways to resolve questions of field line mapping. A series of electron beam rocket experiments led by Winckler demonstrated the feasibility of emitting and imaging an electron beam in space to investigate primarily ionospheric physical mechanisms [Wincker, 1992]. As the spiral of knowledge advances, revisiting active experiments holds a key to finally closing fundamental coupling questions.

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Title: Development and Validation of Space Weather Models using Laboratory Dipole Experiments

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Summary

The capabilities of laboratory dipole plasma experiments have advanced dramatically during the past fifteen years, and today's dipole experiments present remarkable opportunities for the development and validation of Space Weather models of magnetospheric dynamics. Laboratory dipole experiments operate over a wide range of plasma parameters, allow detailed observations spanning global to small spatial scales, and show dynamics relevant to space weather models, including slow and fast plasma convection, centrifugal interchange instability and plasma rotation effects, energetic particle and complex wave-particle dynamics, rapid dipolarization in high-beta plasma, intermittent bursty plasma flows, and fascinating plasma turbulence and transport phenomenon. Laboratory dipole experiments can supplement magnetospheric observations and provide user-controlled experiments with comprehensive measurements that build confidence with predictive models and may discover new insights that enhance our understanding of Space Weather.

Introduction to Laboratory Dipole Experiments

Laboratory dipole experiments have long helped scientists understand space plasma processes and structures [Schindler, 1969; Alfvén, 1975], and laboratory plasma experiments that were configured to have space-relevant particle beams, plasma gradients, and wave-particle interactions have influenced the interpretation of a large number of space observations [Koepke, 2008b]. A series of successful international workshops on the Interrelationship between Plasma Experiments in the Laboratory and in Space [Koepke, 2008a] were held every few years from 1990 through 2005 and fostered a period of interdisciplinary collaboration that advanced fundamental plasma physics and broadened the impact of space physics.

Recently, plasma experiments with strong magnetic dipoles have become operational and achieved a high level of understanding. These experiments have also been built to a very large physical size that, combined with understanding and experience, create a new opportunity for productive and detailed collaboration between scientists developing space weather models and laboratory experiments designed to verify particular aspects of these models. In particular, two of laboratory dipole experiments, one located at the University of Tokyo [Yoshida, 2010] and the other at the M.I.T. [Garnier, 2006b; Boxer, 2010], are made with high-current superconducting dipole magnets that overcome a difficulty that has previously limited the use of laboratory plasmas for the modeling of space plasmas: plasma confined by a laboratory dipole cools rapidly to the magnetic poles. In contrast, new plasma experiments with superconducting dipole magnets can be magnetically levitated. Dense, high-temperature, and collisionless plasma can be created and studied for essentially unlimited observational intervals.

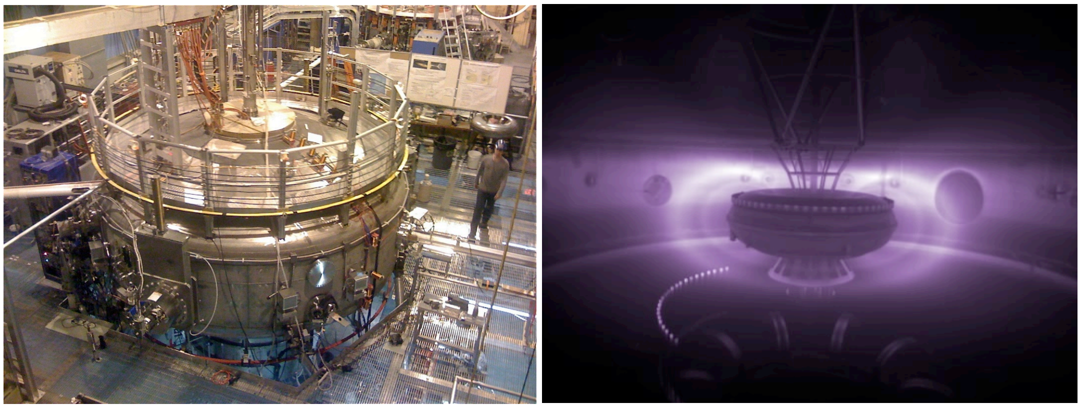

Figure 1. (Left) Photograph of the superconducting levitated dipole experiment at MIT and (right) the hot plasma torus confined by the dipole magnetic field when the dipole is magnetically levitated.

The world's largest laboratory dipole experiment is located at M.I.T. and shown in Fig. 1. This is a substantial research facility containing a strong superconducting dipole that is located within a 5 m diameter vacuum vessel. The superconducting dipole is charged to more than one million Amperes, creating a strong field (exceeding 2.1 T) and magnetizing confined plasma and particles. Another magnet, situated 1.53 m above the superconducting dipole, opposes the dipole's gravitational mass, allowing the formation of hot dense plasma. The dipole position is monitored with an array of eight laser-position detectors, and the levitation current is adjusted with a real-time digital feedback controller capable of maintaining the dipole's position to within $\pm$ 0.5 mm. Plasma is created, heated and sustained by injecting up to 25 kW of microwave power. Multiple frequencies, from 2.45 to 28 GHz, give scientists the tools to adjust the power absorbed at various electron cyclotron resonances in the plasma and, thereby, adjust the electron distribution, and density and pressure profiles.

A major breakthrough discovered with experiments at this size [Garnier, 2006b] is the production of plasmas with an intense belt of energetic electrons with the ratio of plasma pressure to magnetic pressure, β, approaching unity. When scientists injected neutral gas above a threshold (approximately 1 μtorr), intense instabilities [Levitt, 2002; Ortiz, 2007], excited by drift resonances with the energetic electrons, stabilize and allow the plasma pressure and density to rise significantly. When limiters are placed at the poles of the superconducting dipole (so that the magnetic field lines do not pass freely through the coil), the energetic electrons are anisotropic $\beta_\perp / \beta_{||} \sim 5$ and very well-trapped [Karim, 2007]. When the superconducting dipole is levitated without polar limiters, the energetic electrons become more isotropic, but, most significantly, the plasma density and thermal pressure increases substantially. Without polar losses, plasma can only be lost by cross-field turbulent convection (and weak collisions). Measurements of the turbulent electric field intensity predict a time-averaged inward particle pinch that is observed experimentally with an array of microwave interferometers [Boxer, 2010] and is analogous to radiation belt transport driven by random fluctuations of the cross-tail electric field [Birmingham, 1969].

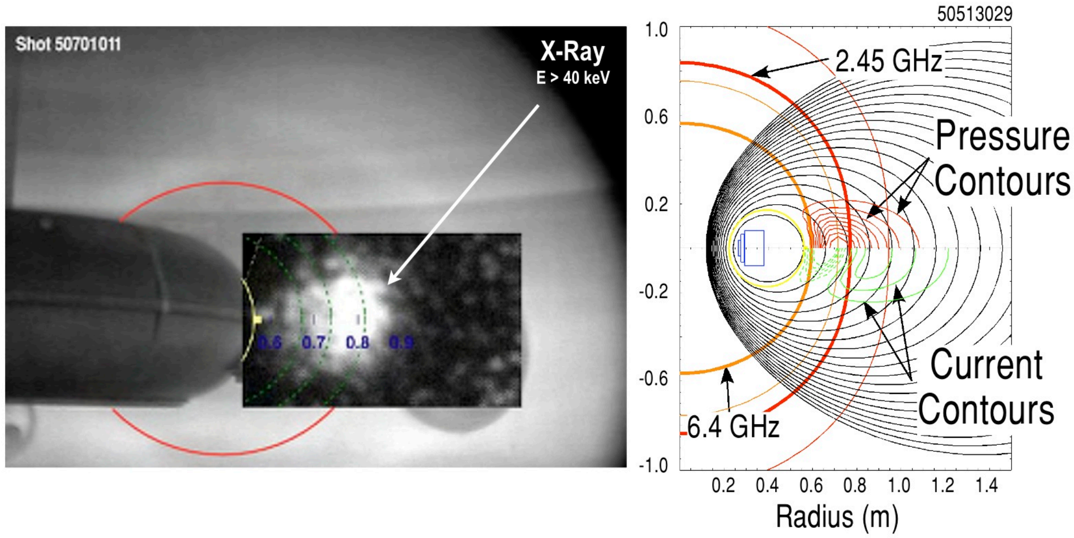

Figure 2. (Left) X-ray image of the energetic electrons created by electron cyclotron resonance and trapped by the dipole magnetic field. (Right) Contours of perpendicular pressure and ring current density computed from magnetic measurements [Karim, 2007].

The large diameter of the experimental apparatus provides unobstructed access for plasma diagnostics and observations. Furthermore, the time-averaged plasma parameters are reproducibly controlled so that measurements can be made repeatedly, throughout the plasma, and for very long time records. Fast, sub-microsecond data records of impulsive phenomenon are made with particle and magnetic field sensors at the plasma boundaries and with line-integrated optical, x-ray, and electromagnetic cyclotron emission diagnostics [Woskov, 2010].

Investigations of laboratory dipole plasma have produced detailed and quantitative understanding of a wide variety of phenomenon relevant to magnetospheric plasma dynamics and space weather modeling. Nonlinear drift-resonance between rotating interchange modes and trapped energetic electrons create chaotic transport [Warren, 1995] or inward spiraling of interchange “bubbles” or “phase-space holes” [Maslovsky, 2003] depending upon the characteristics of interchange wave spectrum. The centrifugal interchange mode is excited when driving rapid plasma rotation that can become sonic [Levitt, 2005]. The low-frequency convection electric fields are dominated by large-scale chaotic structures driven by a quasi-two-dimensional cascade [Grierson, 2009] that induce intermittent, or “bursty”, transport that can be imaged globally and locally [Grierson, 2010].

Opportunities

Large laboratory dipole experiments present a new and exciting opportunity to space weather modelers. For the first time, aspects of the collective and particle dynamics of magnetospheric plasma can be observed in controlled experiments having comprehensive diagnostics. While the entirety of interconnections between the sun, magnetosphere, and

Earth cannot be reproduced in a laboratory device, the fundamental dynamics of trapped particles can be studied systematically. Cost-effective partnerships between modelers and laboratory physicists can lead to model verification through the detailed comparison of dynamical predictions with measurements.

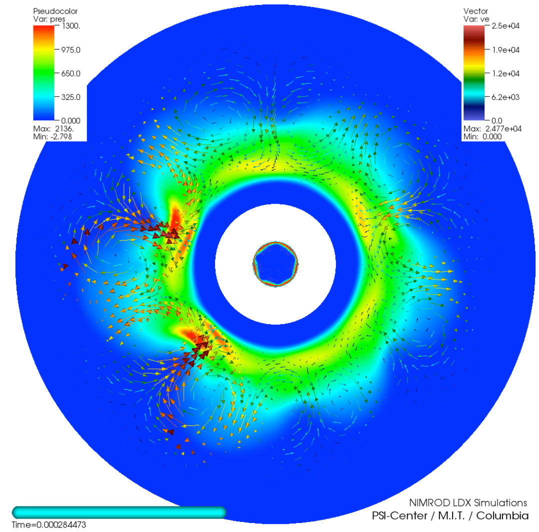

Figure 3. Nonlinear two-fluid, non-ideal simulation of unstable interchange convection of laboratory dipole plasma.

One promising area for space weather verification is the simulation of plasma convection and mixing. Two-fluid, non-ideal simulations [Sovinec, 2004] of interchange mixing driven by steep pressure profiles in a laboratory dipole plasma has recently shown details of the plasma injection/ejection associated with non-axisymmetric convection processes. (See Fig. 3.) These simulations resemble global convection models used for space weather [Toffoletto, 2003]. Relevant experiments include spectroscopic imaging of the convection dynamics of different ionic species, injected from a variety sources and plasma convection conditions. By applying magnetospheric circulation models to specific events and varied dynamics, which are measured in a laboratory dipole plasma, scientists can build confidence in the predictive abilities of these models while also being confronted with the possibility for model refinement and the discovery of additional processes. For example, recent flux-tube simulations of full gyrokinetic dynamics showed clearly how linear drift instabilities, excited by density and temperature gradients, excite secondary Kelvin-Helmholtz mixing and zonal flows followed by saturated drift-wave turbulence that reproduces the particle and thermal pinch observed experimentally [Kobayashi, 2009].

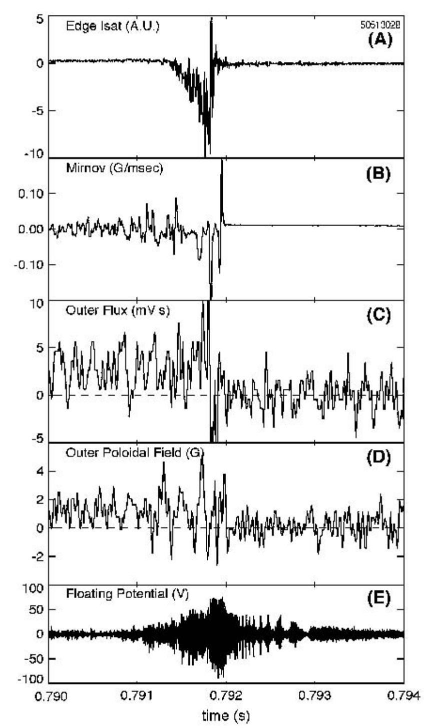

Figure 4. Measurements of fast depolarization event associated with energetic electron transport [Ortiz, 2007].

Another example for collaboration between laboratory measurements and modeling is energetic electron energization [Chen, 2007] and injection [Li, 1998], complex electron cyclotron resonant processes [Cattell, 2008], and transport during depolarization events [Runov, 2009] and geomagnetic storms [Reeves, 2003]. Because laboratory dipole plasmas contain significant populations of energetic trapped electrons (that can become quasi-relativistic), understanding of trapped radiation dynamics in laboratory plasmas can improve understanding of energetic particle events in space. Fig. 4 illustrates a rapid depolarization event caused by rapid radial transport of energetic electrons that results from intense drift-resonant convection [Ortiz, 2007]. In these events, we directly observe electron loss currents with precise time correlations with the electric and magnetic perturbations and bursts of electron cyclotron emission, which we believe to be excited by flux-tubes populated by transported electrons with non-uniform phase-space densities.

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Unexploited heliophysics data sets

Summary

There are several near-Earth space science instruments that are currently returning particle and plasma data from highly-inclined and low-Earth orbit. These are valuable datasets for research into the sources and dynamics of the near-Earth trapped and precipitating particle environments. However they are not adequately available to the space science community despite attempts to make them available.

The SAMPEX mission is being tracked through an engineering program at Goddard, with data processing continuing at The Aerospace Corporation since the end of its science mission in 2004. We were not successful with a recent proposal to extend the data holdings of the SAMPEX data center through 2004 to the present (Kanekal pers. comm. 2009; outline of proposal work plan is attached below), which covers the interesting and deep recent solar minimum and the return of solar activity. For modest resources these data will be made available to the community, making the SAMPEX database one of the longest (18 years and counting) in the history of heliophysics. A recent orbit study put reentry beyond the next solar maximum, thus potentially extending the orbit life to overlap with RBSP.

There are space plasma and energetic particle detectors on board the TWINS mission of opportunity vehicles (referred to as TWINS-ES or environment sensors). The Aerospace Corporation designed, built, and manage these instruments for science and applications uses. They include proton and electron plasma measurements from top-hat electrostatic analyzers [McComas et al. 2009], dosimeters, and an energetic particles instrument that measures trapped and solar protons and heavy ions on TWINS-2. The data are routinely processed but are not widely available. With a modest data processing investment these datasets could be brought to use for the Heliophysics community.

Brief statement of tasks for SAMPEX data center update proposal

We propose to make available the SAMPEX energetic particle database available to the space physics community. These data will be available via the existing SAMPEX data center at http: //www.srl.caltech.edu/sampex/DataCenter/ which currently hosts the SAMPEX data from launch to the end of 2004.

Task Descriptions

1. Port the SAMPEX data processing software from the existing VAX Alpha to a modern UNIX workstation.
2. Validate and verify the full software from Level-1 to Level-2.
3. Process the data from the middle of June 2004 to the present
4. Produce and validate the Level-1 and other data products.

5. Make available all the data and the data products to the public via the SAMPEX data center web site.

Reference

McComas, D. et al., Space Sci Rev (2009) 142: 157–231 DOI 10.1007/s11214-008-9467-4

Center for Magnetosphere and Ionosphere Decoupling Investigations

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Summary

Studies examining the rotated (dawn-dusk) IMF are sparse. Their results, when examined together, suggest that the ionosphere is asymmetric and decoupled from the magnetosphere during rotated IMF, and the magnetic flux is transferred differently during rotated IMF. Current data are not good enough to completely answer the questions raised. Current MHD models can simulate the asymmetric ionospheric conditions, but the ring current and radiation belt models assume polar cap symmetry, which is known to be erroneous. In order to address this lack, an initiative is outlined and a science and technology center is suggested. With a budget of $51Million over 10 years, this initiative would be low cost for potentially transformative results.

Effects of Rotated IMF

Little research has focused on the rotated IMF and its effect on the ionosphere and magnetosphere. In the past, this discrepancy has been explained by noting that geomagnetic activity correlates strongly with the north-south IMF and the magnetosphere-ionosphere system are coupled. Therefore, the rotated (dawn-dusk) IMF should have minimal impact on energy flow into and within the magnetosphere and ionosphere.

Recent work shows these explanations to be incomplete or erroneous. Studies examining the polar cap potential as a function of dawn-dusk IMF have found a correlation [e.g., Mitchell et al., 2010]. Studies examining the Poynting flux in the polar caps have found unexpected amounts of Poynting flux within the lobe cells [e.g., Knipp, private communications; Crooker et al., 1998]. Studies examining the dayside merging line and the possible merging patterns have shown new forms of magnetic field line coupling [e.g., Moore et al., 2002; Watanabe & Sofko, 2009]. Studies examining the relationship between the dawn-dusk IMF and the ring current have found no correlation.

Thus, the rotated (dawn-dusk) IMF is affecting the ionosphere in several ways, but has no observable impact on the inner magnetosphere. This suggests a decoupling of the magnetosphere-ionosphere system. The rotated IMF is also affecting the dayside merging. When viewed in light of combined effects on dayside merging with the possible decoupling of the magnetosphere-ionosphere system, the effect of rotated IMF on the transfer of magnetic flux is seen to be an important area of inquiry for understanding and ultimately predicting the effects of solar storms on the near Earth environment.

Upgrades in the Models and Theories

To examine magnetic flux transfer, magnetospheric response, and ionospheric response to rotated IMF, one might turn to satellite data and a combination of models. Currently, the satellite data is sparse and not in the best locations. The Magnetospheric MultiScale (MMS) mission will aid in providing better satellite data to address the rotated IMF issue. However, further study may show refinements to that mission which would give more complete data.

The current models pose a dilemma. Currently, the MHD models (LFM, BAT-R-US, OpenGGCM) can simulate rotated IMF and global magnetospheric responses. The MHD models simulate both polar caps, which allow the polar caps to be asymmetric in response to the rotated IMF. But the global MHD models do not simulate completely realistic ring current or radiation belts, so they are coupled with kinetic or hybrid models of the ring current and radiation belts.

Ring current and radiation belt models use a single polar cap as input, assuming symmetry between the two polar caps. This assumption negates the MHD modeling of the asymmetric polar caps, and will lead to erroneous results. Modeling with both polar caps requires significant changes to the ring current and radiation belts models.

Advances in the Field of Space Science

A new initiative is recommended to address the need to study rotated IMF and its effects on magnetic flux transfer, the magnetosphere, and the ionosphere. The initiative should stress the importance of understanding all types of magnetic flux transfer, not just those responding to the southward-oriented IMF. The initiative should stress the need to have better models, which could handle asymmetric conditions. The initiative should also stress the importance of the modeling and data communities working in close collaboration to clearly delineate the role of rotated IMF in decoupling the magnetosphere-ionosphere system.

To support this initiative, a science and technology center for studying the decoupling of the magnetosphere and ionosphere should be formed. As a cohesive body of collaborators, the center would provide routine meetings for the modeling, data, and theoretical communities, as well as providing a structured vision with intermediate goals and timelines. It would also allow for a small number of support personnel, such as computer scientists, which could facilitate rapid production of both scientific and operational tools.

The Center for the Magnetosphere and Ionosphere Decoupling Investigations and the initiative outlined above address issues in both the solar wind-magnetosphere interactions and the atmosphere-ionosphere-magnetosphere interactions panels. The center and initiative also meet requirements of the NASA Heliophysics Roadmap, addressing several research focus areas (e.g., F1, F2, H2, and H3). The expected cost is approximately $51Million over a 10-year period. The cost is calculated by taking the approximate cost of a previous science and technology center and applying inflation.

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NASA's Explorer Program as a Vital Element to Further Heliophysics Research

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Introduction

This White Paper will make the case for an enhanced Explorer program as a vital program element for Heliophysics. The Explorer program has been one of the greatest success stories of NASA since its very beginning. Explorers, which include stand-alone missions of various sizes as well as the Explorer-run Missions of Opportunity (MoOs), are PI-led missions that have returned outstanding discoveries. Missions, such as COBE, AMPTE, SAMPEX, FAST, ACE, TRACE, WMAP, RHESSI, THEMIS, and most recently IBEX, have produced breakthrough science results. This program is vital to an extraordinary range of science in both the Heliophysics and Astrophysics science programs. It is the only competed mission line that has consistently offered relatively frequent opportunities to carry out small missions with well-focused science goals. These missions are developed and launched in a short (approximately three to four-year) timeframe. Several of the missions have led to breakthrough results in Heliophysics, such as the Interstellar Boundary Explorer (IBEX) with its first all-sky maps of the heliospheric boundary and the discovery of the "Ribbon" as a marker of the surrounding interstellar magnetic field orientation.

For the health of the field, it is important to maintain a steady stream of small missions between the increasingly sparse large mission opportunities. Also, these PI-led missions have historically stayed within budget and on schedule. It is also worth noting that in the most recent Senior Review the TWINS mission, one of the Explorer Missions of

Opportunity, was rated #1 in science per dollar among all 13 heliospheric missions under consideration. Therefore, we call for an increase in the Explorer Budget so that on average one launch per year is achieved again, with the typical accessibility of 50% of the missions being Heliophysics missions.

This white paper is applicable to all three Decadal Survey study panels.

Discussion

Explorer Missions have successfully spearheaded science topics that range from the Earth's atmosphere, auroral regions, magnetospheric substorms via the Sun and the boundary of our solar system with the interstellar medium to most distant luminous objects in the universe at an overall cost that is well below those of larger scale missions. ISEE has provided deep insight into particle acceleration and transport through the magnetosphere and has enabled the first ever encounter with a comet; AMPTE has pioneered active experiments in the solar wind and advanced composition observations throughout the magnetosphere; FAST has re-written the understanding of auroral phenomena; ACE has taken solar wind, interstellar, solar energetic particle, and cosmic ray composition to the next level and in the process changed several paradigms about solar and galactic cosmic rays; TRACE has provided detailed insight into chromospheric and coronal structures on the Sun; RHESSI has provided unprecedented solar flare diagnostics; and IBEX is changing the paradigms of the heliosphere-interstellar medium interaction. As is evidenced by the frequency of these missions, the Explorer program was intended to provide frequent and rapid access to space in order to be able to react to new promising and important scientific ideas. However, over the past decade the rate at which Explorers are initiated has substantially diminished.

Simultaneously over the last few decades, increased launch and mission costs have reduced the launch rate for all SMD missions, in particular, the larger mission lines. Already now, there are only a few places in the country left that are capable of supporting a flight instrument development and implementation. This is particularly true for space science groups at universities, where other large-scale developments are not present as, for example, in large research centers. The remaining hardware centers at universities are in constant danger of losing valuable engineers and technicians from their just barely critical skill mix, since they don't have any cushion to balance a "bursty" funding profile, which can become particularly uneven through very few large hardware programs. Having access to a reasonable rate of Explorer opportunities would be an important element to smooth the potential funding flow.

The Explorer Program has not only provided the opportunity to take up important focused investigations on a reasonably paced schedule, it has also been a determining factor in many scientific careers in Heliophysics, and has provided graduate and undergraduate students at participating universities with an invaluable training ground. The reason is that participation in Explorer programs has been much more in line with the mission and capabilities of university laboratories than the ever-increasing requirements for large missions. Therefore, increased access to Explorer opportunities will also provide a valuable training ground for NASA's technical base, with its ability to attract and train young talent.

Implementation and Cost

Currently, the Explorer line contains a mix of Small and Mid-Size Explorers and a separate SALMON (Stand-Alone Mission of Opportunity) component that provides the means to join forces with other agencies and/or other nations' space programs. Therefore, this mix of sizes and opportunities should be maintained. However, the overall program should be restored to the effort level of the late 1990's through the early 2000's. In 2001, the Explorer budget was approximately $140M. The FY11 budget request for Explorers is only $120M, which is still a large improvement in the funding over the last four or five years. However, to restore the Explorer program to its earlier level would require a budget of more than $170M, after adjusting for inflation.

Conclusion

Heliophysics has derived a number of its successes and breakthroughs in the past from successful Explorer missions. To remain innovative and maintain a healthy program with a steady stream of observations, punctuated by a high frequency of new opportunities, the field needs a mix of large missions and small PI-led frequent mission opportunities. This mix is also needed to maintain a diverse infrastructure in the field that includes viable university centers and to train the future generation of engineers and scientists. Such a balanced approach can be achieved by a targeted increase in the Explorer funding so that on average a launch rate of one mission per year is reached again. The required funding increase is of the order of $50M per year over last year's funding level.

Laboratory for Active Space Experiment Research (LASER) Program

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"By no amount of reasoning can we altogether eliminate contingency from our world … We must eliminate some of the conflicting possibilities, and this can be brought about only by ***experiment*** *and observation."*
— Morris Raphael Cohen

1. Summary

A case is presented for the resumption of active space experimentation in Heliophysics. A review of the history of such experiments indicates important successes, and a survey of known concepts for future experiments suggests outstanding opportunities. Programmatic considerations suggest that a program patterned on the Explorer Program, but devoted to using space as a Laboratory for Active Space Experiment Research (LASER), would be the best means for identifying and developing such experiments in the future. The LASER Program will cultivate and enable a renewal of active space experimentation that resolves persistent problems of space phenomena and allows definitive interpretations based on hypotheses that would otherwise be untestable.

2. Description

Our variable Sun produces a wide range of conditions that drive all the known space phenomena, allowing opportunities for exploration and study of their behavior within a large and multidimensional space of possibilities. Nevertheless, many of the variables are correlated within the framework of the heliosphere, so that these systems are not free to explore all possible states in which they could conceivably exist. Thus, as always, the most fundamental tests of understanding are produced through the performance of experiments in which selected variables are actively controlled, and the consequences are measured. The history of active space experiments has been mixed, but on balance, much has been learned from such experiments. It would appear that enthusiasm for active experiments declined sharply during the years of the Space Transportation System (STS). Because of its lift capacity and the possibility of astronaut tending of experiments, the shuttle was to have been a boon to space experiments, at least in the ionosphere. But, ultimately, the high cost of shuttle missions was incompatible with the budgets available for space science, and the Spacelab series of planned experiments was cut short before the Space Plasma Laboratory, planned for the 1990 timeframe, could fly. The thesis here is that the termination of the STS program represents an opportunity for reconsideration of active space experimentation, with formation of a new initiative in this area, in which geospace is identified as a laboratory for active space experiment research.

As examples of notable past successes of active space experiments, consider the following:

A. The Starfish Prime program was an defense-motivated experiment in which a high altitude nuclear test was conducted in July 1962. The resulting artificial radiation belts eventually crippled on third of all satellites in low Earth orbit, amounting to seven satellites failure over several month, including the first communications satellite, Telstar. The artificial radiation reported on by *Brown et al., [1963]*. Though this particular experiment holds little attraction to repeat, and would never again be permitted, a great deal was learned from it. However, the mitigation of radiation from the belts remains of great interest (see below).

B. Ionospheric release experiments with Barium, Strontium and Calcium have confirmed the critical ionization velocity effect, allowed measurement of ionospheric convective motions and calibrated electric field measurements *[Wescott, et al. 1994]*.

C. High altitude release (tracer) experiments like the Active Magnetospheric Particle Tracer Experiment (AMPTE) produced a famously negative result for tracer entry from the solar wind, and also provided the only complete data set on energetic ion spectra, composition and charge state throughout the near-earth magnetosphere [*Krimigis, et al.,* 1983]. Altogether, it carried out eight major active ion releases: two releases of clouds of lithium ions in the solar wind in front of the magnetosphere, barium "artificial comet" releases in the dawn and dusk magnetosheaths, and two each releases of lithium and barium ions in the near magnetotail. The results presaged our current understanding of localized and reconnection-dependent solar wind entry into the magnetosphere, with substantial contributions from Earth's atmosphere via the ionosphere.

D. Electron beam experiments like the Echo series *[Winckler, 1980]* and SEPAC *[Burch et al., 1994]* demonstrated that keV electrons behave collisionlessly enough to make a transit to the conjugate hemisphere, be mirrored and return to the emitting payload region where they are then detectable if the payload tracks the local convective motion. These experiments established a basis for future beam experiments and also presaged the development of the Electron Drift Instrument flown on the Cluster mission as a new way to measure the convection electric field and local magnetic field conditions.

E. Plasma Diagnostic Probes like that flown on the STS have shown that spacecraft behave like artificial comets in the interaction of their outgassing volatiles with the orbital speed ionospheric flow *[Paterson and Frank, 1989; Gurnett et al., 1988]*. When this outgassing is sufficient, pickup ions are created by the electric field in the orbiter frame of reference, and these pickup ions relax (and eventually thermalize) via the production of highly non-thermal power law tails extending to 10's to 100's of eV. This behavior is analogous to the interaction of the inner cometary coma with the shocked solar wind.

3. Cost

This white paper presents no specific mission for consideration by the Decadal Survey. Rather, it suggests Decadal Survey advocacy of a NASA initiative to conduct active experiments in space. The specific experiments to be performed would be selected through an open community competition of ideas, along the lines of the existing Explorer program. Whereas the Explorer program seeks mission concepts of discovery, the LASER program would seek mission concepts that actively test and discriminate between proposed interpretations of phenomena that have been discovered by Explorer and other missions.

Active experiment concepts known to be under discussion and subjects of proposals from the Heliophysics community include at least the following:

A. Ionospheric heater experiments: These experiments have been ongoing for some time and are capable of marked heating of the ionospheric plasma. Usually performed in a sub-auroral context where the ionosphere is otherwise quiescent, they provide definitive tests of the physics of plasma wave - particle interactions in a tightly controlled manner. In principle, ion species can be heated selectively.

B. High altitude electron beam experiments: Experiments have been proposed to fire an electron beam from a high altitude, near equatorial location that is conjugate with auroral regions where the magnetic field is highly variable and uncertain in its connectivity. Thus, a central purpose of such an experiment would be to determine definitively the connection point in the ionosphere by creating an observable feature there, either in optical emission or via a radar signature. Given this capability, the time dynamics of magnetic connections between the geosynchronous region, for example, and the conjugate ionosphere, could be tracked during magnetospheric disturbances. This information would allow the first definitive tests of field models of that magnetic geometry.

C. High velocity, high energy release experiments: The release of cold gas moving at high velocity through the topside ionosphere creates a situation that is highly analogous, differing only by a frame shift, to the auroral context in which the magnetosphere drives the ionospheric plasma through the thermospheric gas at high velocity, though not ordinarily as high as orbital or escape speeds. In this situation, pickup ion distributions are formed with toroidal initial velocity distributions. These must relax initially via plasma wave emission and velocity diffusion, as observed by the PDP on the space shuttle. This process is poorly understood theoretically, for lack of definitive observations of the process in action.

D. Radiation belt mitigation experiments: Given any threat of high altitude thermonuclear explosions, and our high dependence upon orbital assets, there is great interest within the defense establishment in the possible mitigation of the radiation belts in manner timely enough to avoid damage to our fleet of satellites. Any method for generating intense whistler waves in the radiation belt region may be a candidate for such mitigation. Experiments based on various methods for generating the appropriate waves have been conceived to test the effectiveness of such methods. This is an area with very high interest levels in both curiosity driven science and applications.

4. Relevance

LASER addresses the relevance criteria cited by the Decadal Survey panels, as follows:

a. It has not been a high priority programmatic target, but should be, for reasons given above.

b. It cuts across all NRC panel themes, at least in principle, pending development of specific experiment concepts.

c. It addresses, in principle, all scientific questions facing solar and space physics today, as identified in the 2003 Decadal survey and 2009 Heliophysics Roadmap:

d. It contributes to applications and-or policy making to the degree that the selected experimental investigations do so. Clearly this would be an important priority as it is for the Explorer program.

e. It complements and indeed is dependent upon ground observational systems including optical spectral imaging and radar observations of geospace.

f. The cost of a LASER program to resolve these problems would be similar to Explorer program costs.

g. It is at a readiness level (technical, resources, staffing) that supports implementation.

h. LASER is synergistic with other national and international plans and activities, such as the National Space Weather Program, and other Heliophysics programs such as the STP, LWS, Explorer, and SR&T Programs. It also would be synergistic with DoD programs intended to explore methods for radiation belt mitigation.

5. Conclusion

Whereas, active experimentation is of compelling importance in elevating Physics above “mere stamp collecting” (quote attributed to E. Rutherford); and whereas, the documented track record that active space experiments have accumulated during the space age is an impressive achievement; and whereas, the STS program is shutting down and in any case should no longer exert any exclusive domain over active experiments in space; and whereas, a number of interesting and compelling concepts for active experimentation are known to exist in the Heliophysics community:

Be it therefore resolved that:

A space mission program for active experiments should be undertaken by NASA, tentatively known as the Laboratory for Active Space Experiment Research, or LASER program.

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Long-term monitoring of the global space environment

Paul O'Brien, The Aerospace Corporation

Long term monitoring is essential to understanding geophysical phenomenon. This truth has been demonstrated repeatedly by ground-based observatories, whether meteorological, seismic, or geomagnetic. Long-term monitoring of geospace remains haphazard: NOAA maintains sophisticated sensors on POES in LEO and GOES at GEO, and various national security satellites carry in situ sensors. However, no comprehensive strategy exists to ensure that significant events, such as the March 1991 shock or the March 1989 superstorm, are adequately observed. The good fortune of having the CRRES spacecraft on orbit during the March 1991 event led to numerous advances in scientific understanding of the radiation belts. The March 1989, which preceded CRRES, yielded far fewer advances in our understanding, as it was primarily observed only by ground-based sensors. More recently, the July 2004 storm produced the most intense >2 MeV electron fluxes ever observed at geosynchronous orbit, exceeding the predicted worst case flux by more than 100%. Every 11-year solar cycle presents its own unique, idiosyncratic extreme events, and no two solar cycles are alike. Without a concerted strategy to ensure adequate, continuous monitoring, advancement of scientific understanding of extreme events depends entirely on good fortune.

For the foreseeable future, communications, navigation, scientific and national security satellites will continue to operate in the Earth's inner magnetosphere. The energetic particles encountered by spacecraft in the inner magnetosphere pose a number of hazards, including surface material degradation, total dose degradation of electronics, single event effects, surface charging, and internal charging. These hazards pose a well-known operational challenge – they can cause satellite anomalies. For satellite operators to have situational awareness, and to ultimately understand the cause of anomalies, requires knowledge of the space environment everywhere that satellites fly, all the time. The space environment hazards also pose a satellite design challenge. Satellite designers must characterize the mean and worst case environments against which they will trade risk and mitigation (e.g., shielding and redundancy). Because of the long correlation times associated with high energy particles (e.g., 1-2 years for the transient radiation belt formed in March 1991), proper characterization of extremes, and, in some cases, means, is nearly impossible without continuous, long-term monitoring. Therefore, as society becomes ever more dependent on satellite technology, it is incumbent on the scientific community to understand and characterize the long-term environment, and its extreme behavior.

To a large degree, the long term variation of the inner magnetosphere has been characterized by low earth orbit (LEO) and geosynchronous (GEO) spacecraft operated by NOAA, the DoD and the DoE, with a few exceptional NASA, ESA, and other explorers. Since these latter explorers have been funded entirely as science missions, they have tended to be small in number and short in duration. Thus, to a large degree the region between low earth orbit and geosynchronous orbit remains underexplored. NASA plans to remedy this situation with its Radiation Belt Storm Probes mission (RBSP). However, RBSP is committed to a design that limits its life to approximately 4 years. Therefore, after RBSP, there will again be no in situ measurements of large portions of the energetic particle population – the ring current and radiation belts. One solution to this problem is a GOES-like sensor package on a satellite in geosynchronous transfer orbit GTO. A low-inclination GTO is ideal because the trajectories of trapped charged particles carry them through the magnetic equator as they drift around Earth, allowing a single satellite to map a 3-D volume. A Transfer Orbit Environment Satellite (TOES) would augment the successful POES and GOES lines, and fill in a valuable spatial hole in their monitoring capabilities. Such a satellite could carry instruments that meet the GOES-R SEISS requirements, but which would be modified to operate successfully in the harsher radiation environments found in GTO. In particular, a hybrid of SEISS and RBSP sensors could meet the particle measurement requirements. It would also be valuable to include some of the electromagnetic wave and field measurements that RBSP includes, since many of the outstanding scientific questions about the inner magnetosphere depend on the behavior of both particles and fields during extreme events – for example, understanding of the CRRES shock event was greatly facilitated by on-board field measurements. Since every GOES vehicle passes through GTO on its way to its permanent station, it would be logical to drop off a TOES sub-satellite along the way.

The similarity between RBSP and TOES suggests another potential path to long-term monitoring: a NASA-NOAA handoff. In such a scenario, NASA would continue to develop explorer missions like RBSP, THEMIS, and SAMPEX, with the goal, where appropriate, of handing over the mission to NOAA for long-term operations once the main or extended science mission ends. SAMPEX continues to operate, some 6 years after NASA ceased maintaining it as an active science mission. The scientific and operational value of SAMPEX data over that past 6 years is immense, and yet they are nearly unexploited because SAMPEX is no longer an active NASA mission. The primary change from NASA's perspective would be that certain satellite design choices might have to be made with an eye toward long-term (post-mission) operations. The cost to NOAA of assuming operational responsibility for a mission that is already on orbit and whose operations are already demonstrated and well-defined should be minimal.

A monitoring mission capable of making long-term, high-quality, uncontaminated measurements of the energetic particles and electromagnetic fields in the Earth's inner magnetosphere would pave the way for greater scientific understanding and superior technical mitigation of one of the most extreme space environments in the inner solar system.

The Heliophysics Data Environment as an Enabler of HP Science of the Next Decade

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Summary

Heliophysics science requires efficient, long-term access to well-maintained repositories of carefully prepared, documented, and preserved data to "develop an integrated research strategy that will present means to address [high-priority scientific] targets," as required in the charter for this Decadal Survey. Because of this, we strongly urge the decadal committee to:

(1) reaffirm support for the "Solar and Space Physics Information System" recommended in the last decadal report, and that has been moving forward due to the efforts of many countries and agencies;
(2) assert the importance to the accomplishment of science goals of adequate and sustained funding for agency efforts to maintain and further improve long-term archive and distribution mechanisms; and
(3) strongly support the need for general standards for archiving and distribution of data as exemplified by those contained in the NASA Heliophysics Science Data Management Policy, and starting with the endorsement of an open data policy by all relevant agencies.

Introduction and Goals

Research in Heliophysics (HP) now routinely involves working with many instruments, often in different space- or ground-based observatories, correlated with various time lags and interpreted or predicted by simulations and theory. Data from decades ago, such as from the Helios spacecraft to the inner heliosphere or the CRRES mission through the radiation belts, are still frequently used to examine questions of intrinsic importance and for planning of new missions such as Solar Probe Plus or the Radiation Belt Storm Probes. The testing and improvement of models of the magnetosphere require data from DoD spacecraft (such as DMSP and TWINS), NSF and international collections of ground-based instruments (e.g., the magnetometer network seen in SuperMAG), and from a large fleet of spacecraft from Japan (e.g., Geotail), Europe (the four Cluster spacecraft, for example), NASA (Wind, Polar, THEMIS, etc.), and other nations. Studies of the Sun using the rich new data from the Solar Dynamics Observatory only realize their full potential when used in conjunction with data from Hinode, STEREO, other spacecraft, and a variety of ground based telescopes. **Thus, we have a strong need for a coordinated, easy to use, international, long-term data environment to exploit the available resources to solve the problems facing Heliophysics in the next decade. Recent developments have both brought us much closer to this goal and point the way toward more powerful techniques to come.**

At the time of the previous decadal survey, Heliophysics data systems were improving in a piecemeal fashion, but there was no overall plan for going forward. At NASA, the open data policy and the increasing emphasis on data plans in Senior Reviews of extended missions were generally making data more available and easier to use. Data were increasingly becoming available online from US and international space- and earth-based observatories. However, there were no explicit guidelines for what data and metadata were to be captured and how they were to be served and preserved. Since then, much has been achieved in attaining a goal of the previous Decadal Survey, as part of the Vitality Program, that stated a requirement for a

> "Solar and Space Physics Information System: Multiagency program for integration of multiple data sets and models in a system accessible by the entire solar and Space Physics community."

The goal of this White Paper is to argue for the continuing need to support a Heliophysics Information System as essential to HP research, and to indicate how recent developments are making Heliophysics data increasingly easy to use and supportive of the needs of current research. **Given the many diverse groups involved in this system, the integration of the HP Data Environment must be based on shared standards, rather than on direct consolidation. The most important "standard" is the acceptance of an open data policy by all providers of HP data.**

The above-recommended Vitality Program activity has been advanced by a number of initiatives. One early significant effort was the establishment of the international Space Physics Archive Search and Extract consortium in 2001 to encourage interoperability and develop a common "data model" to provide uniform descriptions of Heliophysics data products. This effort continues to be supported by NASA. This was followed by one of the most important initiatives, the institution in 2007 of a NASA Heliophysics Science Data Management Policy and its subsequent significant revision in 2009 (http://hpde.gsfc.nasa.gov/Heliophysics_Data_Policy_2009Apr12.html). This Policy codified many *de facto* practices and provided the basis for clarification and advancement of the HP Science Information System as envisioned in the Decadal Survey. The flow of data from spacecraft to final archive and from server to end-user is described. The Data Policy specifies the requirements and expectations for Project Data Management Plans, Mission Archive Plans, Resident and Final Archives, Virtual Observatories, and data/metadata standards. The basic set of groups and functions have been or were already established within NASA to accomplish the goals of the Data Policy. New missions are using the Policy to guide their efforts, and older missions are now largely compliant with it. We have yet to realize the full potential of new approaches such as Virtual Observatories, but the groundwork has been laid. The Data Policy has facilitated interactions with other agencies (especially NOAA and NSF) and with international partners in Japan, Canada, Europe, and other countries, and it has been used for guidance in the planning of similar policies outside of NASA.

NASA Heliophysics has been committed to stable funding of the NASA HP Data Environment, as described in the Data Policy, and it is crucial for the success of essential multifaceted and long-term scientific studies that this support and that of other agencies be continued.

The rest of this White Paper provides information on the need for an HP Information System, and the current status, plans, and needs of the Heliophysics Data Environment (HPDE; see also http://hpde.gsfc.nasa.gov), with the emphasis on NASA's role but with indications of the essential and coordinated roles played by many others.

Historical and Scientific Motivation

Initial observational efforts in Space Physics consisted of a team flying their own experiment in space. The results would become known to the rest of the community and the general public through meetings, press conferences, and publications, but the data were not generally shared, and there were no standards for formats if they were. Thus we learned of the existence of radiation belts, the solar wind, the Earth's bow shock, solar coronal holes, and the other now familiar aspects of the heliosphere through a series of carefully designed instruments sent out to a wide variety of locations with no clear sense of how or when the data might be shared. It was recognized early on that the data thus gathered were unique and irreplaceable, so provisions were made for a National Space Science Data Center to save them and to document their formats, but often, while the bits were preserved, the utility of the data declined rapidly after the end of the mission due to the difficulty of reading and using what were essentially proprietary datasets. A number of these datasets have been reformatted for general use over the decades since their production. When the expertise was available, they have been reprocessed and improved, and they are now easily web-accessible, typically as ASCII or CDF files. One goal of the current HP Data Environment is to avoid the need to recover data, but rather to have them seamlessly pass to long-term active archives.

Subsequent missions gathered time series and images that have become increasingly like long-term weather station and imagery records of the Earth's weather and climate, but now for the history and dynamics of the Sun, heliosphere, magnetospheres, and the near-planet plasma environments. Scientific questions have progressed from determining the elements of the heliophysical system to determining both the small-scale details of the physics (e.g., how magnetic fields reconnect to release energy in flows, waves, and energetic particles) on the one hand, and the global interactions of the various components (such as how Coronal Mass Ejections form, propagate through space producing energetic particles, and interact with the Earth to generate magnetic and particle storms) on the other. Both of these kinds of investigation require substantial coordination of data from multiple instruments, multiple spacecraft, and comparisons of these with simulation results and theory. For example, much deeper understanding of reconnection and its role in the magnetosphere has come from simulations combined with detailed studies of the data from many instruments on the four Cluster spacecraft for the microphysics, and from the many instruments on the five THEMIS spacecraft combined with other spacecraft studies and ground-based observations of magnetic fields, aurora, and auroral winds for the large-scale picture. In this way we have come to appreciate, for example, the role of electrons in the small-scale processes and the sequences of reconnection and energization of the near-Earth fields and particles.

Establishing a vibrant, robust and agile data environment is an essential element of an integrated research strategy capable of addressing the science targets identified by the Decadal Survey. The creation of the Heliophysics Information System is guided by efforts in other science domains. Progress in the Earth Sciences has been greatly aided by the use of a uniform data format for the large missions, namely HDF (which now incorporates NetCDF) and the provision of data from distributed but uniformly accessible sites. The connections to data have been enhanced by the adoption of OPeNDAP as a protocol for data transfer that allows users to bring data directly into their favorite analysis applications so they can apply their own tools or those from libraries developed by others. A similar development has occurred in Astronomy where the US Virtual Astronomical Observatory and the International Virtual Observatory Alliance have set standards for data, metadata, transfer protocols, and other aspects of the data system that now allow astronomers to call up previous observations of any object in the sky or to do complex correlations over large sets of objects defined by user-selected criteria. This promises to revolutionize the types of studies possible, and thus to greatly deepen insight on, for example, the evolution of stars and galaxies. These types of capabilities, with similar potential for aiding research, are now on the horizon for Heliophysics, with core capabilities already in place.

Current Status of the Heliophysics Data Environment

The HPDE consists of a set of related data and modeling systems that are becoming increasingly interconnected. Large, active repositories of data from old and new observatories and programs are held at NOAA's NGDC; NASA's SPDF, SDAC, and NSSDC (data) and CCMC (models); JAXA's DARTS; the European CDPP; various NSF locations such as the SuperMAG and CEDAR/VSTO sites; and at a large set of active mission repositories in many countries. An increasingly complete set of these data sources is being registered in uniform terms that can be easily searched and accessed (see below). There has been considerable convergence on data formats, making data use much easier. Data are flowing in a natural way into post-mission archives, although in some cases clearer paths need to be mapped out. The current HP Information System is functioning well, delivering large volumes of data to researchers in useful ways.

In addition to the formulation of a NASA HP Data Policy, a number of complementary developments have considerably advanced the Data Environment. The last two NASA HP mission Senior Reviews required each mission to provide a Mission Archive Plan (specified in the Data Policy) that detailed the products, documentation, formats, and dissemination methods of the mission data for the long term. In each review, new datasets were produced and better documented, and the plans have become progressively clearer. Thus, the active missions now are, for the most part, producing highly useable products for the long term. New NASA missions, such as RBSP and MMS are taking the Data Policy to heart, following the PDMP guidelines and planning for appropriate description and archiving of data. Other datasets are becoming more unified, such as the NSF, NASA, and internationally sponsored ground-based magnetometer chains that are now largely united by the SuperMAG project that is sponsored by both NSF and NASA.

The uniformity required for data descriptions to be useful is now being supplied by the "SPASE" Data Model (http://www.spase-group.org) that consists of a uniform set of terms and an implementation (in XML) that allows us to describe and access products and services from all Heliophysics disciplines, wherever they are located throughout the world. This Data Model is the result of many years of collaboration by a representative group from many US and foreign organizations including NASA, NOAA, and many universities; there are now SPASE data model adopters in Europe, Japan, and Canada in addition to NASA Heliophysics Virtual Observatories and Data Centers. Within the next two years, NASA's Space Physics Data Facility, in its role as a NASA Active Archive, plans to have an essentially complete set of high-level product and service descriptions, made available through the Virtual Space Physics Observatory (http://vspo.gsfc.nasa.gov) as a registry. It is already possible to locate and access data from most of the current and many past Heliophysics missions. The NASA HP Virtual Observatories work with missions and archives, and in particular providing a contact point for new missions, to provide more detailed descriptions of the complete set of products to assure that products will be scientifically useable based on the SPASE metadata. Some NSF-based products (such as ground magnetometers) are now registered in SPASE terms, and informal arrangements have been made for NOAA and NASA to help NSF to serve and preserve datasets produced by NSF Space Physics projects. On the solar physics side, the Solar Data Analysis Center has been working with recent missions to provide access to data both directly and through the Virtual Solar Observatory that unites access to a very wide range of solar physics products, including all the products from the ESA/NASA SOHO mission, the two STEREO spacecraft, and the huge data volumes coming from the Solar Dynamics Observatory. Uniform VSO access complements mission specific access to data.

Plans

The distributed HP Information System expects to continue to archive and provide access to an increasingly complete set of data from observations and complementary models. Funding should continue to be provided so that older datasets will be upgraded to be better and more accessible when deemed important. As missions terminate, data will flow into post-mission archives, and standards for archival formats are being established more clearly (e.g., there is a plan to make CDF a true NASA archival standard, to join FITS and HDF/NetCDF). Datasets will continue to be registered in SPASE terms, and made accessible through Virtual Observatories as unifying portals. This general unification will enable a wider range of easy cross-dataset and data-model comparisons than now possible, as well as other services such as searching for data across many missions with a query based on time, location, event or feature lists, the values of particular quantities, or the similarity of target events to chosen events; the efficiency and depth of these sorts of services are potentially transformative in the science that is possible. The progress toward uniform access and the associated growth in possible tools will take place in many US agencies as well as in collaboration with international partners. An example of the latter is the work in progress involving the European "HELIO" project and the US HP Virtual Observatories. Much of what must be done consists of adopting common standards or of finding ways to do rapid translations between systems.

Needs

The Heliophysics Data Environment, now being unified through a partly formal, partly informal Heliophysics Information System, requires a basic level of support to realize its goals. The current level of NASA and other funding, if it remains stable as intended by the current NASA HP managers, is sufficient for the basic needs of the data system, but allows little room for much beyond that. New demands will come from the need to archive large datasets, such as those from recent solar physics missions and upcoming multispacecraft Space Physics missions, and from the related need to support tools for more sophisticated data mining, feature recognition, and other services that will be facilitated by the integration of the data environment. The total funding for HP Data Centers and related data system activities at NASA (outside of mission budgets) amounts to about 1% of the NASA Heliophysics budget, which seems a small price to pay for the benefits. Modest funding increases to preserve and make effective use of the rapidly growing data volumes are warranted to obtain the potential benefits from the data.

In terms of organization, it will be important to continue the work to establish interagency and international standards and collaboration. We should encourage DoD and DoE, along with all other agencies that produce data of importance to Heliophysics, to agree on a general data release policy that safeguards any national security concerns while adhering to an open data policy. Fledgling associations, such as the informal agreement for NASA and NOAA to aid NSF in archiving space physics data, should be recognized at the agency levels as being important and thus encouraged to flourish, and these should be expanded to include all relevant agencies responsible for data provision. Similarly, international efforts to unify standards and increase interoperability through agreements on data and metadata formats and communication protocols should be endorsed and made part of the working environment of each of the constituent groups.

Acronyms and Glossary

CCMC: Community Coordinated Modeling Center, sponsored by NASA, NSF, the Air Force and other agencies; provides runs on demand and works to transition models to operational space weather use.

CDF: Common Data Format, a self-documenting format increasingly used for the storage and serving of Space Physics data, developed and maintained by the SPDF.

CDPP: Centre de Données de Physique des Plasmas, the French national active archive of Space Physics data.

CRRES: Combined Release and Radiation Effects Satellite, investigated the radiation environment of the inner and outer radiation belts, 1990-1991.

DARTS: Data ARchives and Transmission System, JAXA's active archive for Space Physics (and other) data.

HDF/NetCDF: Hierarchical Data Format, a self-documenting format used for storage and serving of Earth Science and related data, e.g., for ionospheric spacecraft data.

Helios: A pair of spacecraft that explored the inner heliosphere from 0.3 to 1 AU, 1975-1981.

Hinode: A Japanese/US spacecraft that provides high temporal and spatial resolution images of the Sun in a variety of wavelengths, launched in 2006.

DMSP: Defense Meteorological Satellite Program, a series of DoD meteorological satellites that have particle sensors relevant to Space Physics.

FITS: Flexible Image Transport System, a file format used for solar and astrophysical image data.

HELIO: HELiophysics Integrated Observatory, a European consortium (with US involvement) concerned with uniform access to HP data, based on both simple and complex search criteria.

HP: Heliophysics

HPDE: Heliophysics Data Environment, a collective term for the datasets, repositories, access methods, and other services associated with the scientifically relevant output from HP observatories and instruments.

JAXA: Japanese Aerospace Exploration Agency

NGDC: National Geophysical Data Center, NOAA's source for Heliophysics (and other) data.

NOAA: National Oceanic and Atmospheric Administration

NSSDC: National Space Science Data Center, a safe-keeping, "deep" archive for HP data; provides long-term backup services to, e.g., SPDF, among other functions.

Polar, Earth orbiting spacecraft, 1996-2008, that imaged the aurora and measured in situ particles and fields

SDAC: Solar Data Analysis Center, a NASA HP designated Active Final Archive for Solar data; serves solar data from many current and past missions.

SPASE: Space Physics Archive, Search, and Extract, an international collaboration that has produced a Heliophyics Data Model that allows the uniform registration and use of HP data and services.

SPDF: NASA's Space Physics Data Facility, the primary NASA Active Final Archive for Space Physics data, home to data systems such as CDAWeb and OMNIWeb.

STEREO: Solar TErrestrial RElations Observatory, a pair of Sun orbiting spacecraft that image and measure the particles from Coronal Mass Objections and other solar activity, lunched in 2007.

THEMIS: Time History of Events and Macroscale Interactions during Substorms, a set of five spacecraft studying magnetic and particle activity in the magnetosphere, launched in 2007.

TWINS: Two Wide-angle Imaging Neutral-atom Spectrometers, a pair of instruments on non-NASA spacecraft that use stereo energetic neutral atom images to study the Earth's ring current, launched in 2008.

Wind: A spacecraft that measures the solar wind fields and particles upstream of the Earth, launched in 1994

SuperMAG: A worldwide collaboration of ground-based magnetometers, supported by NSF and NASA.

WHITE PAPER FOR THE
HELIOPHYSICS SCIENCE DECADAL SURVEY, 2013-2023.

The Case for Exploring Uranus' Magnetosphere.

This White Paper is endorsed by 66 scientists (listed at the end) from the USA and Europe, many of whom are early career scientists representing the driving force of the heliophysics community in the decades to come.

Motivation.

In order to further our understanding of how life and the platforms for life exist in the wide variety of magnetic environments in the Universe it is vital that we make comprehensive measurements in the widest possible variety of environments. **Our Solar System provides the only local laboratory in which we can perform experiments that are helping us to understand the nature of planetary magnetospheres in general.**

A White Paper submitted to the Planetary Science Decadal Survey 2013-2023 [*Hofstadter et al*.] provides a persuasive case for a Uranus orbiter to investigate the composition, structure, atmosphere and internal dynamo of the planet and the nature and stability of its moon and ring system. They advocate a New Frontiers type mission with 2020-2022 being a particularly efficient launch window. The proposed mission is exciting, exploratory and timely given that the 'ice giants' are the only major category of Solar System object never to have had a dedicated mission. In that plan, powerful arguments for a magnetospheric element to such a mission were overlooked. Here we outline the science case for a dedicated magnetospheric mission to Uranus, one that could go in tandem with, or be combined with, the proposed planetary orbiter.

We also note that a "Uranus Pathfinder" mission, which does include strong magnetospheric elements, is being proposed by *Arridge et al.* to the European Space Agency. Given the cost of these missions and the evident excitement across the planetary and heliophysics communities for such a mission, it seems sensible to coordinate our efforts over the coming decade, both within NASA and between NASA and ESA. We the undersigned advocate strong support in the Heliophysics Decadal Survey for the magnetospheric science opportunities associated with a Uranus (or Neptune) orbital mission.

Background.

The Uranian system has a unique configuration among the planets because its axis of rotation lies nearly in the ecliptic plane. Its north and south poles lie where most planets have their equators, and its tenuous rings are almost perpendicular to its orbital plane. In addition to the unconventional spin orientation, the Uranian magnetic dipole axis is tilted at the unusually large angle ~ 60° from its spin axis. Figure 1 illustrates the configuration that exists near Uranian solstice, appropriate to the Voyager 2 encounter in 1986. The next Uranian solstice occurs in 2028, a few years before the earliest feasible arrival time for a Uranus orbital mission.

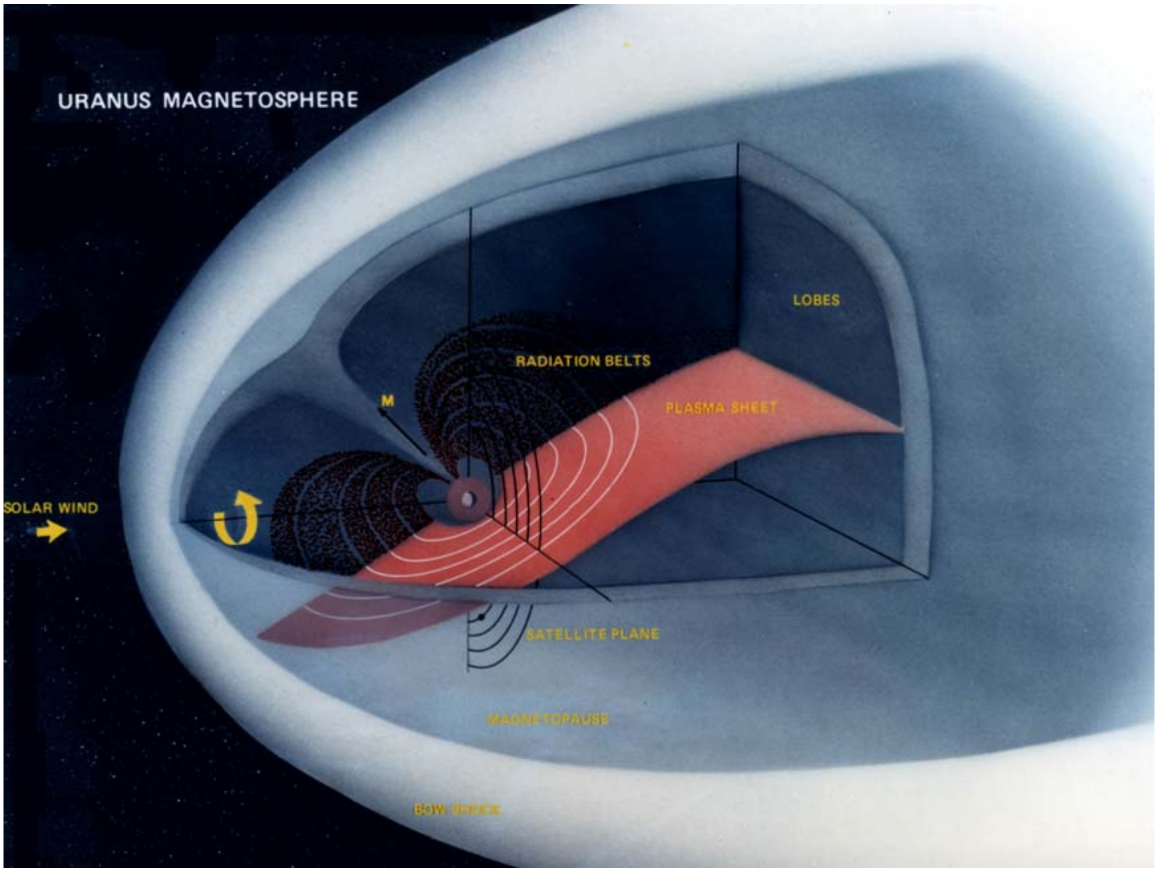

Figure 1. Overview sketch of the Uranian magnetosphere showing bow shock and magnetopause, boundary layer, dayside cusp, satellite plane, plasma sheet (shaded), radiation belts, and extended hydrogen atmosphere around Uranus. The magnetic and rotation axes are marked. From *Krimigis et al*., 1986.

Given the strength of the magnetic field at Uranus and the fairly rapid rotation rate, one might expect to find that the Uranian magnetosphere is rotation-driven like those of Jupiter and Saturn [*e.g*., *Bagenal*, 1992; *Vasyliūnas*, 2004]. In fact, **Voyager 2 observations were more nearly consistent with a classic solar-wind-driven magnetospheric convection system like that of Earth.** This can be explained by the fact that, near solstice, a solar-wind-driven magnetospheric convection system would be orthogonal to, and thus unimpeded by, planetary rotation [*Vasyliūnas*, 1986; *Hill*, 1986; *Selesnick and Richardson*, 1986]. Because its flyby trajectory was close to the ecliptic plane, the Voyager spacecraft was unable to observe the plasma properties in the ring plane (or in the magnetic equatorial plane) inside an *L* value of about 12.

The unique magnetospheric configuration at Uranus provides the opportunity to investigate several aspects of plasma production, energization, transport, and satellite interactions that, despite several decades of study, are still not fully understood. These include the following specific top-level questions:

1. Magnetospheric transport.

The peculiar combination of magnetic and spin axes means that the plasma sheet is twisted as the planet rotates. Voyager measured the magnetotail to ~400 Uranus radii behind the planet. The extreme tilt of the magnetic axis, combined with the tilt of the rotational axis, causes the field lines in the roughly cylindrical magnetotail to be wound into a helical (corkscrew) shape [*Hill et* *al.*, 1983]. Otherwise well understood mechanisms for plasma transport and diffusion have never been studied in this type of geometry. **How does plasma move radially in this type of configuration?**

The unique feature of the Voyager 2 encounter was the fact that the spin axis of Uranus was aligned nearly along the planet-sun line. This led to the condition that a solar-wind-driven magnetospheric convection system was effectively decoupled from corotation, as noted above. Stated another way, the flow system rotational electric field, which ordinarily would have "shielded" the middle magnetosphere from the solar wind, was oriented in such a way that solar wind effects could penetrate deeply into the magnetosphere. The consequences included:

a) Convection patterns similar to Earth's with a well defined plasma pause.
b) Strong dynamics including Earthlike injection phenomena;
c) An electron radiation belt that was as intense as the most intense seen at Earth; and
d) The strongest whistler-mode emissions seen at any of the outer planets.

By the time that a new Uranus orbiter mission might reach Uranus, this pole-on configuration would no longer prevail exactly, and would become less applicable as the mission progresses. The mission could thus address the following fundamental questions: **When the solar-wind-induced and rotational motions become less decoupled, will Uranus' magnetosphere become more quiescent, like that of Neptune, or will it become more rotation-driven, like those of Jupiter and Saturn? Will it show injections as were seen during the Voyager encounter? Will the radiation belts be equally intense? What will convection look like?**

2. Energetic particle trapping.
One might expect that the configuration at Uranus would lead to less efficient particle trapping and heating required to form radiation belts. In fact, Voyager 2 found electron radiation belts at Uranus of intensity similar to those at Earth and much more intense than those at Saturn. The ion radiation belts are similar between Uranus and Saturn, although they differ in composition. **How stable are the Uranian radiation belts? Are they always present? Are they devoid of heavy ions, and if so, why? What are the relative roles of moon sweeping and wave-particle interactions in limiting the radiation belt fluxes? How far inward do these belts extend towards the rings and upper atmosphere of Uranus?**

3. Neutral particle dynamics
Neutral gas and dust are critical components of magnetospheres as currently shown with recent Cassini research of the Saturnian system. Such particles not only provide sources of magnetospheric material but also modify magnetospheric dynamics though interactions with charged particles and the planetary magnetic field. No other planetary system allows for neutral particles, rings and moons (rotating around the planetary spin axis) to interact with magnetic fields and plasma at such large oblique angles (60 degrees). This should create highly dynamic and previously unobserved types of particle interactions. Additionally, ring particles can retain an electric charge and interaction with an offset magnetic field should hinder ring stability and yet these rings exist at Uranus. **With the high inclination of the Keplerian plane versus the magnetic equator at Uranus the dynamics of neutral gas and dust as they are formed and redistributed throughout the magnetosphere are likely to be complex and provide insight**

into sources and magnetospheric evolution as well as providing critical insight in magnetospheric stability and dynamics.

4. Satellite weathering.
The radiation belts of Uranus appear to be dominated by hydrogen ions, without any evidence of heavier ions that might have been released from the surfaces of the moons. Uranus' radiation belts are so intense that proton irradiation would quickly darken (within 100,000 years) any methane trapped in the icy surfaces of the inner moons and ring particles. This may have contributed to the darkened surfaces of the moons and ring particles.

Only limited information has been available about the weathering of the Uranian satellites. At the time of the Voyager 2 encounter, there was discussion about the nature of the dark material on these bodies and the possible role that charged-particle weathering has in darkening the ice. One proposal was that, if a small fraction of methane were present in the ice, weathering by charged particles could darken ice grains by the creation of carbonaceous material (*Cheng and Lanzerotti* 1978). However, *Veverka et al*. (1991) pointed out that, despite the absolute albedoes, the only surface constituent that was observed spectrally was water ice which should produce a bighter albedo. This seemed to call into question the presence of methane. *Cheng et al.* (1991) later argued that heavy processing of the top layer by ions would alter the surface so much that it would not have methane ice spectral features. While this remains an open question, other lines of thinking have suggested that the darkening is purely due to geology, and that weathering is a secondary effect. *Grundy et al.* (2003) recently identified leading/trailing differences on the surfaces of the Uranian satellites. **Leading/trailing asymmetries are suggestive of processing by grains, plasma, or energetic charged particles. The relative importance of these effects are yet to be resolved, and in situ observations of magnetospheric particles and plasma are necessary to unravel the causes of the observed surface differences.**

5. Daily variability.
Overall configuration and stability of the Uranian magnetosphere: What are the 3D magnetic and plasma properties of the main regions and their boundaries of the asymmetric magnetosphere of Uranus? Do these regions contain quasi-steady or transient particle populations**? How does this exotic magnetosphere reconfigure during a Uranian day?**

6. Seasonal variability.
The Uranian seasonal changes are completely unlike those of the other major planets. Near Uranian solstices, one pole faces the Sun continuously while the other pole faces away (this was the case during the Voyage encounter). Only a narrow strip around the equator experiences a rapid day-night cycle, but with the Sun very low over the horizon as in the Earth's polar regions. At the opposite side of its orbit, the orientation of the poles is reversed, so that each pole gets around 42 years of continuous sunlight, followed by 42 years of darkness. Near equinox, the Sun faces the equator of Uranus, giving a period of day-night cycles (on the order of 17 hours) similar to those seen on most of the other planets. Uranus reached its most recent equinox in 2007. The next solstice will happen in 2028, and the next equinox in 2049. An orbital mission launched around 2020 would reach Uranus shortly after its 2028 solstice and could be expected to observe it during the approach to its 2049 equinox. **The effect of the equinox geometry at Uranus on magnetospheric configuration and stability is entirely unknown.**

Measurement requirements.

In their White Paper *Hofstadter et al.* describe the science drivers for several measurements including high resolution magnetometery, microwave sounding, multi-wavelength imaging and spectroscopy, along with laboratory and ground based support measurements. They note that a single spacecraft would be more cost effective (based on a high-level study done at JPL) and that significant science payloads could be inserted into orbit around Uranus using chemical propulsion alone using relatively modest launch vehicles. Thus cost is the single biggest factor limiting instrument payload size making cost sharing across disciplines and internationally a very attractive option in producing a feasible cost-effective mission.

We advocate the inclusion of a dedicated magnetospheric element, ideally on a spinning platform, to be included on, or go in tandem with, a planetary mission to Uranus and ideally in collaboration with ESA. Additional instrumentation would ideally include:

Ion plasma composition and full electron pitch angle distributions across the widest possible dynamic range (a combination sensor akin to the JEDI-JADE plasma suite on the Juno spacecraft might be most appropriate).

Radio and plasma wave package with similar capabilities to those onboard the Cassini (RPWS) and Juno (WAVES) spacecraft.

Neutral particles and dust detectors (something like the Cassini INMS and CDA instruments).

An additional high resolution **magnetometer** (like the Cassini MAG) would be required if the magnetospheric platform is a separate platform.

A companion White Paper by *Hess et al.* outlines how a dedicated magnetospheric mission can fit under a New Frontiers type costing. We add our support to that White Paper and further endorse that the community endeavour to perform such a mission in collaboration with the Planetary Science and international (ESA) community.

A final note, while the science outlined here is motivated by our desire to make un-paralelled magnetospheric measurements at Uranus, the tour phase out to 20 AU will afford a rare opportunity to make solar wind observations in the outer heliosphere and as such appeal to an even broader section of the heliophysics community.

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The Case for Continued, Multi-Point Measurements in Space Science

A White Paper Submitted to the NRC 2010 Decadal Survey in Solar and Heliospheric Physics

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It is now 50 years since the start of the space age. In the beginning, every new launch brought new observations and new discoveries: the plasma environment above the neutral atmosphere, the extra-terrestrial radiation source(s), the magnetosphere, the radiation belts, the magnetopause, the bow shock, and the supersonic solar wind. Still, the discoveries continue. The discovery of new physics and subsequent scientific study over decades has raised far more questions than it has answered. With every new measurement and improved understanding multiple new questions are generated. While there remain fundamental discoveries yet to be made, the bulk of the space science discipline is now reaching a state of maturity where progress is made at a more detailed level. Taking nothing away from the latest missions and the newest observations, it is increasingly clear that to perform good science requires complimentary measurements from multiple points analyzed in combination with advanced numerical simulation and evolving theory.

The purpose of this paper is to argue three simple points:

1. Measurements from multiple, often widely spaced, locations are essential to provide the context needed to study the physics of the large, coupled space environment system.
2. Measurements over long time baselines that provide the most varied physical conditions provide the insight needed to see new or underlying physics that is obscured by observations that are too narrowly limited in scope.
3. Measurements from multiple, widely spaced, locations are required to support new missions making discovery measurements.

In addition to these points, we argue that new measurements are needed in old locations to make measurements at previously unresolved spatial scales or unmeasured energy ranges that will provide new insights to solve old problems.

Multi-point measurements are essential to science. Nowhere is this point made more clearly than in the magnetosphere where knowledge of the solar wind input is critical to understanding the magnetospheric response. Additionally, the largely subsonic flow conditions mean that all regions of the magnetosphere contribute to responses and dynamics at a single point. Much of magnetospheric physics is inherently non-local and widely separated multi-point measurements are essential to unravel the physics that defines this region.

Long baseline measurements are essential to science. The recent protracted solar minimum has provided unexpected new observations in solar wind and heliospheric magnetic field physics that challenge preconceived ideas of a solar minimum rest state, minimum interplanetary magnetic field flux levels, and baseline solar wind flux. These things were never predicted and they are seen in defiance of popular theories. Moreover, it is doubtful that NASA would have provided a mission for the specific purpose of studying solar minimum primarily because the recent new results were unanticipated and there was no warning of impending new science.

The extended period of low solar activity has had consequences for energetic particle studies as well. The galactic cosmic ray (GCR) intensities have reached levels higher than ever before measured in space. Small, isolated solar energetic particle (SEP) events have been observed simultaneously by spacecraft separated in longitude well beyond the previously assumed longitudinal spread of such events. Measured anomalous cosmic ray (ACR) gradients during the extended period of high current-sheet tilt indicate their transport in the inner heliosphere is not due to rapid drift along the current sheet. Such unexpected observations over a wide energy range and resulting multi-spacecraft measurements can only be possible by spacecraft providing long baseline measurements spanning many years. These observations provide new insights and new questions for old missions with possible roles for new missions that were unanticipated previously.

Existing assets must be preserved for the simple reason that we can not adequately predict future new results in space science. Accepted paradigms are challenged when new conditions result in new measurements made by old assets. Only long baseline measurements spanning the most diverse conditions can reveal the true underlying physics governing any physical system.

New missions require multi-point support measurements. In an era where new small missions cost $300M and major missions cost $1B, there are limits to what can be flown. Pre-existing instruments and missions provide all of the contextual information required to do new science with old missions PLUS they support the new missions in the very same manner. No physical process (whether it is reconnection, particle acceleration, or the dynamics of global structure) can be pursued with local measurements alone and here the support of new missions falls on the shoulders of pre-existing hardware.

One of the most recent, notable examples of this is STEREO. Pre-existing assets at L1 are positioned to provide both a third point of solar longitude when studying transients or energetic particles as well "ground truth" for any predictions that STEREO may provide for Earth-approaching transients.

Understanding the longitudinal distribution of energetic particles, the structure and extent of interplanetary shocks and other magnetic/solar wind structures requires measurements at sufficiently separate locations. Relating these observations to space weather and their impact on the Earth requires measurements along the Sun-Earth line (e.g., at L1).

NASA's policy of making all data publicly available has resulted in enhanced science returns for all missions. For example, over 75% of all publications using ACE data do not involve an ACE/SWT member and this is the way it should be. Most missions have similar statistics. These "outside" authors extend the application of the data beyond the initial intents of the spacecraft team, diversify the science return, and build largely on multi-spacecraft, multi-point data analyses. NASA has spent decades and many millions of dollars building the in situ fleet we now enjoy and it must be maintained now or it will be lost for generations.

The Sun-Earth Environment

The physics of the Sun-Earth environment is far more complicated than that of isolated, non-interacting dynamical processes. Remote solar observations by SOHO, WIND, RHESSI, STEREO, and SDO not to mention numerous ground-based assets, reveal a high degree of magnetic structure at all scales in the photosphere and solar corona. Solar wind sources mimic the large-scale magnetic structure of the Sun with the polar holes being major contributors and numerous low-latitude structures providing what is thought to be slow wind sources. Numerous solar models attempt to predict the 3D structure of the solar wind, but no attempts to date provide accurate and reproducible results. Multiple platforms such as ACE, WIND and STEREO are needed to test and refine these efforts. Erupting magnetic structures (CMEs) show a high degree of internal consistency in the solar wind, but they propagate through a structured solar wind showing massive large-scale structure as well as poorly studied small-scale structure. Energetic particle acceleration may reflect at least a comparable degree of structure, but inadequate spacecraft separation during times of high activity has made these studies virtually impossible. Solar wind magnetic structure on small scales may mimic the solar source, but many more studies are needed.

Diverse conditions drive new science. We have learned things about the solar wind during the recent, protracted solar minimum that were not predicted earlier: the solar wind density and flux is lower than previously seen and the IMF is weaker. Previous predictions for a minimum IMF intensity have been swept away. Both depletions exist at all latitudes of the heliosphere. Solar wind composition has changed. Comparing long baseline measurements and multi-platform observations provide the insights needed to form new theories as we resolve solar sources. At the same time the magnetosphere has entered a state not seen before. Without solar wind drivers the transient dynamics are different. The radiation belts have almost disappeared. This provides new insights and new questions for old missions. Without the older missions, we would be unaware of these unanticipated new results.

Old missions provide context for new missions. It is well established that magnetospheric science is today well-served by reliable L1 measurements characterizing the solar wind input. New missions (such as RBSP and MMS) require contextual observations to understand their own time-dependent observations. These contextual measurements include solar wind (ACE and WIND) as well as magnetospheric missions (GOES) and ground-based observations.

Interplanetary Solar Wind Studies

Every study of interplanetary dynamics has left us with new challenges and every answer has spawned new questions. The twin platforms of STEREO were launched to better understand transient dynamics from launch through interplanetary propagation, but the launch into the most protracted solar minimum of the space age has delayed many of those goals. Simulations teach us much on these topics, but they must be tempered by observations. On smaller scales, the pairing of ACE and WIND has provided new insights into medium-scale shock curvature and associated particle acceleration dynamics while additional pairings with Geotail, Cluster and Themis provide new insights into solar wind turbulence over scales from the correlation length down to dissipation scales. Single spacecraft measurements are incapable of providing these insights.

Missions deliberately designed and created as multi-platform investigations (Cluster and MMS) will serve many purposes in addition to their original goals. Cluster is now providing new insights into small-scale solar wind turbulence and MMS will eventually do the same at yet smaller scales. However, the bulk of the multi-platform studies come not from these missions, but from the fortuitous combination of pre-existing assets at greater spatial separation. Whether the topic is turbulence, transients, or energetic particles, the Earth-orbiting and L1 assets together with more distant planetary and interplanetary missions provide the necessary associated measurements linking solar wind studies at all spatial and temporal scales. The subject could be as small as inertial range turbulence or as large as the formation of GMIRs and the related galactic cosmic ray solar cycle: the many separate assets of space physics form the largest and most versatile of the great observatories.

Planetary Studies

No one can deny the ground-breaking discoveries of the ongoing planetary missions. Undeniably, these are discovery missions in the truest sense. However, the purpose and application of these missions will also evolve with time. Once moons are mapped and their properties determined, once the radiation environments are better understood, once the planetary magnetospheric structure is determined, planetary science will turn to the type of studies now being performed in the Earth's magnetosphere – the mature study and understanding of the complex fields and currents that constitute the near-Earth (or near-planet) environment. Again, multi-point measurements will be required to achieve this understanding and while new multi-platform studies within the planetary magnetospheres will be desirable, these multi-point studies will begin with measurements of the solar wind and the resulting input into the planetary environment. This purpose will probably be served in the near-term by 1 AU missions.

Heliospheric Physics

The last decade and the most recent years have seen an unprecedented exploration of the heliosphere. Voyagers 1 & 2 have crossed the termination shock and have begun to penetrate the heliosheath. In the process they have raised new questions regarding the acceleration of anomalous cosmic rays and the propagation of galactic cosmic rays while also revising our understanding of the entire sheath region. IBEX has imaged the interstellar boundary region at all heliographic latitudes and longitudes and found signatures of previously unexpected interactions with the local interstellar medium. New Horizons is on its way to join the outer heliospheric fleet. None of these measurements could be properly understood without near-Sun baseline measurements of the solar wind and solar activity. The changing ram pressure of the solar wind, together with changing levels of transient activity, determines the location of the termination shock and a significant fraction of the heliosheath dynamics (the still-unmeasured interstellar medium determining the other fraction).

New Measurements

There is no denial that new measurements propel space science forward with the greatest impulse. No one is arguing against the development of new missions. However, new measurements without the context of simultaneous multi-point observations offer only limited value and are subject to greater misinterpretation or overly aggressive speculation. The good science, the solid science of the 21st century requires the greatest range of observations to provide the greatest scientific return on the investment.

Summary

Of necessity, every statement in this brief 7-page document is both incomplete and inadequate. We have attempted to remind the committee of the most undeniable fact that the pursuit of modern space science requires diverse, separated, long-term measurements. We have failed to do justice to any single mission. For instance, IBEX, which we describe as imaging the interstellar boundary region, has also imaged the Earth's magnetosphere, and lunar dynamics as well as interplanetary shocks. This gives IBEX a place in the study of the local Sun-Earth environment. This type of multi-tasking, multi-purpose application of resources is typical of the space physics assets today and similar statements can be made for virtually all missions.

These things are central to understanding the heliophysics system (Sun to Earth to Interstellar Space):

- Long baseline measurements and new conditions provide new relevance to older missions.
- Every observation benefits from the context provided by other instruments and other missions.
- New missions making original measurements require other spacecraft for context.

The astrophysics community responded to the need for new data by defining "Great Observatories" and these have made new and exciting measurements. For in situ heliospheric physics the single Great Observatory is the fleet of technically diverse and spatially separated missions that provide the measurements needed to understand the coupled nonlinear subsystems that together form the whole of the heliosphere.

Solar Wind Kinetic Physics
High Time Resolution Solar Wind Measurements from the DSCOVR Mission

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The 1 AU, near-Earth solar wind has been observed by a number of NASA and international spacecraft over the past decades. However, particle instrumentation technology limitations did not allow the direct observation of the varying properties of the thermal solar wind particles in the kinetic regime, which requires measurements with better than 1 Hz cadence. Observations at this kinetic scale are essential to understand how the solar wind is continuously heated as it propagates away from the Sun, how small scale magnetic reconnection operates in the 1 AU solar wind, and how interplanetary shocks can accelerate particles to high energies. The DSCOVR mission, to be refurbished at NOAA expense and launched by the USAF, gives a unique opportunity to NASA to obtain unprecedented time resolution solar wind measurements for a minimal cost. The DSCOVR spacecraft is already built (see Figure 1) and requires only an 18 month refurbishment to be ready for an operational space weather and scientific research mission.

1. SCIENCE OBJECTIVES

Figure 1. The DSCOVR spacecraft in a Goddard SFC clean room.

The classical theory of the solar wind predicts an expansion of a hot corona reaching high asymptotic speeds with no further heating deposition [*Parker*, 1963]. On the other hand, we have known for some time (e.g., *Parker* [1964a,b]) that some form of heating, starting somewhere near the base of the corona and extending into interplanetary space, is required to generate the high asymptotic wind speeds characteristic of the fast wind. Furthermore, in-situ satellite measurements of the electron and ion temperature profiles from 0.3 AU to 1 AU fall-off more slowly with radial distance than those theoretically predicted by thermodynamics (see *Cranmer et al.* [2009] for a summary of Helios and Ulysses observations illustrating this effect), suggesting some form of local heating. This non-adiabatic heating is likely to be an extension of the non-adiabatic coronal heating that is a necessary ingredient of the acceleration of the fast solar wind [*Parker*, 1964a,b]. Thus the solar wind plasma is far from local thermodynamic equilibrium and electron and ion velocity distributions deviate significantly from local Maxwellians wherever they have been observed (e.g., see the review by *Marsch* [2006]), Thus, properly computing the solar wind temperature from the base of the corona through the solar wind acceleration region will require understanding an assortment of plasma kinetic processes which contribute to the generation and regulation of these non-thermal plasma populations.

How do turbulent fluctuations at the Larmor radii or inertial length scales heat the particle velocity distributions?

There is broad consensus that magnetohydrodynamic (MHD) turbulence plays an important role to the local heating of the solar wind (e.g., *Vasquez et al.* [2007], *Cranmer et al.* [2009]). The basic physical picture is that large scale "energy containing" eddies (e.g., posited that the differential motions of adjacent streams are unstable to the generation of large scale Alfvén waves as suggested by *Coleman* [1968]) recursively cascade to smaller scales until reaching a dissipation scale which is determined by wave-particle resonances [*Howes et al.*, 2008a, b; *Schekochihin et al*., 2009]. While much progress has been made in understanding the physics of the cascade in the inertial range (below the driving scale and above the dissipation scale), a clear picture of the dissipation process has not yet emerged. In particular, we do not understand exactly how the energy in the small scale fluctuating fields and flows is converted into internal energy. To answer this question we need to measure the density, temperature and anisotropy of both ions and electrons at cadences faster than 1 s to be able to estimate these fluctuations on length-scales of the order of the Larmor radii and on the inertial scales for both ions and electrons. These measurements have not been made in the long history of near-Earth solar wind research.

What physical processes and conditions control the dissipation-scale spectral break of the interplanetary magnetic field?

The spectrum of magnetic field fluctuations in the solar wind is approximately a power law spectrum from 10^{-4} Hz to 10^{-1} Hz with a typical power-law exponent near 5/3. This inertial range spectrum is followed by a spectral break, a steepening of the spectral slope that typically occurs around 1 Hz in the spacecraft frame at 1 AU. The spectral break is believed to be caused by the onset of collisionless damping at kinetic scales which converts turbulent energy into particle thermal energy (*Leamon et al*., 1998a,b, 1999a,b, 2000). The length scales that mark the transition from large MHD scales to small kinetic scales are the thermal ion cyclotron radius and the ion inertial length. If the fluctuations are primarily composed of Alfven waves propagating parallel to the mean magnetic field B_0, then strong ion cyclotron damping of the left-hand polarized mode occurs when their wavelengths become of the order of the ion-inertial length and this condition will determine the location of the spectral break. On the other hand, if the fluctuations are composed primarily of quasi-perpendicular propagating waves, then there is a transition from the Alfven wave to the kinetic Alfven wave (KAW) when their wavelengths become of the order of the ion-gyroradii and this is the wave number where collisionless (i.e., Landau) damping starts to become significant and the spectral break occurs. Closely related to these mechanisms are the kinetic processes and plasma instabilities that regulate particle distribution functions in the solar wind, many of which remain controversial (*Hellinger et al*., 2006; *Bale et al*., 2009). To address this question we need, besides the density, temperature and anisotropy of the solar wind ions and electrons at these temporal scales, a determination of the wave vector propagation relative to the local magnetic field. To provide closure, the bulk velocity measurements have to have enough temporal resolution to allow for Doppler shifting (if necessary) the observed frequencies into the rest frame of the plasma, measurements that have not been made to date.

How does the electron halo and *strahl* form?

Electrons have been usually considered less important than the ions for the dynamics of the solar wind, because of their small mass and occasional lower thermal energy density. However, electrons are essential to ensure quasi-neutrality, and are the main contributors to the ambipolar electric field via the thermal pressure gradient. They can carry energy in the form of heat-flux driven by the skewed thermal bulk and/or a suprathermal tail of the velocity distribution function. These electron properties are determined mainly by the large-scale interplanetary magnetic field and the self-generated electrostatic potential, by Coulomb collisions in the thermal energy range of ~ 10 eV, and by various other kind of wave-particle interactions. The solar wind electrons are also subsonic, i.e., their solar wind mean speed is considerably lower than their mean thermal speed. Their velocity distribution function, as illustrated in Figure 2, typically include a cold quasi-isotropic Maxwellian core, a hot halo with a power-law like distribution (usually well-modeled by a Tsallis-Lorentzian κ-like distribution function) that sometimes could be anisotropic, and a distinct field-aligned beam called the *strahl*, which carries most of the electron heat flux.

The classical Spitzer-Härm heat law states that the electron heat flux flows down the local temperature gradient. If this is valid at the base of the corona, then some mechanism must be depositing heat into the corona to maintain the local maximum. However, the ratio of the mean free path to the temperature gradient scale at the coronal base is such that non-local transport effects can render the Spitzer-Härm perturbation theory invalid. *Dorelli and Scudder* [2003] have demonstrated (by numerically solving the Fokker-Planck equation) the surprising result that significant non-thermal electron distributions can be maintained at the base of the corona in the presence of Coulomb collisions, in some cases allowing heat to flow *up* the local temperature gradient.

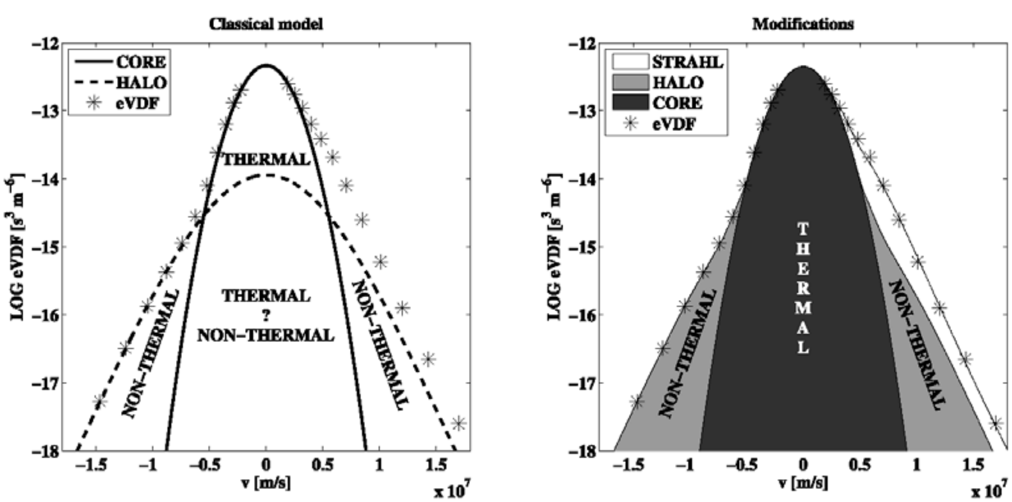

Figure 2. Components of the electron velocity distribution function.

Several processes begin to contribute to the solar wind thermal conductivity as particles move out from the coronal base into interplanetary space along a magnetic flux tube. If the solar wind were completely collisionless, electrons at the coronal base with enough energy to traverse the polarization potential barrier (required to maintain zero radial current density) would be focused into a very narrow beam aligned along the magnetic field. This would form the *strahl* component that indeed has routinely been observed in the fast solar wind from 0.3-1 AU (e.g., *Schwenn and*

Marsch [1991]). But the observed *strahl* component is typically broader than that predicted by magnetic moment conservation alone. In particular, we do not understand exactly how does the *strahl* broaden and how is it regulated. Observations suggest that the formation of the solar wind halo electrons is the result of the scattering of the *strahl* (*Maksimovic et al*. [2005]; *Stverak et. al*., 2009). The premise is founded on observations that connect the decrease in the *strahl* density with radial distance from the Sun with a corresponding increase in the density of the halo. Whether this is due to a long term steady scattering of the *strahl* or occurs in multiple short bursts is not known, nor has there yet been a scattering mechanism identified. To identify this mechanism, sufficiently fast cadence (~ 1 Hz at 1 AU) full electron distribution function measurements in the 1 AU solar wind are necessary.

Another effect that shapes the electron heat flux is the polarization electric field, which acts to decelerate electrons (producing a population of trapped electrons with zero bulk velocity in the Sun's rest frame) and accelerate protons (e.g., *Jockers* [1970], *Lemaire and Scherer* [1972], *Maksimovic* [1997]). In the context of the steady state Vlasov equation, the polarization electric field is the mechanism by which the solar wind protons are accelerated to supersonic speeds. A major difficulty with such collisionless models, however, is that they do not properly take into account the effects of microturbulence driven by the large (unobserved) anisotropies and velocity space discontinuities which tend to occur in steady state Vlasov solutions. And indeed, this electron deceleration process might be closely related to the problem of the broad "strahl" component, also requiring unprecedented ~1 Hz full electron distribution function measurements in the 1 AU solar wind.

Are there small, bursty magnetic reconnection events in the 1 AU solar wind?

Very narrow regions in the interplanetary medium where magnetic field strength abruptly decreases to nearly zero, have been observed for a long time [e.g., *Burlaga and Ness*, 1968; *Burlaga*, 1968], and have been termed magnetic holes by *Turner et al*. [1977]. Two major classes of these magnetic holes have been distinguished: "D-sheets" associated with field rotations [*Burlaga and Ness*, 1968] and "linear' magnetic holes [*Turner et al*., 1977; *Fitzenreiter and Burlaga*, 1978] which show no field rotations. D-sheets are of particularly great interest since they might be the interplanetary signatures of small, bursty reconnection events. Linear magnetic holes on the other hand are believed to be pressure-balanced structures. However, to date, no sufficiently high time resolution solar wind plasma data is available to study these structures. Magnetic holes near Earth, which are not infrequent with a rate of about 1.5/day, move past a spacecraft in the time range of 2 to 130 seconds, the median time being 50 seconds. Thus plasma measurements with a cadence of at least 1 second is required, in conjunction with similarly fast magnetic field observations, to provide the first detailed observations of the internal structure of magnetic holes that would lead to a greater understanding of the magnetic reconnection mechanism.

What is the internal kinetic structure of interplanetary shocks?

While interplanetary shocks have been studies for a very long time, and even the internal structure of MHD shocks is comparatively well understood primarily due to Earth bow shock observations, very little is known about the structural variations due to the various MHD shock types. The nearly stationary Earth's bow shock provides an excellent opportunity to study of fast reverse strong MHD shocks. However, the much richer variety of interplanetary shocks are much harder to study due to their great speed with respect to, and hence short time of passing, a spacecraft. High time resolution (< 1 second) plasma and magnetic field observations are required to open a window into the internal structures of weak and even slow interplanetary shocks hopefully leading to a better understanding of their formation, dissipation and their acceleration of energetic particles.

2. THE DSCOVR SPACE SCIENCE INSTRUMENTATION

The science questions outlined above have it in common that they all require high time resolution (< 1 second) 1 AU solar wind ion moment, full electron distribution and vector magnetic field measurements. The Deep Space Climate Observatory (DSCOVR), formerly known as Triana, spacecraft has a space science instrument package, called PlasMag, that meets these measurement requirements. The PlasMag suite consists of three parts: 1) a Faraday cup to measure the reduced distribution function of the ion component of the solar wind with an unprecedented time resolution of 90 milliseconds, 2) a "tophat" electrostatic analyzer to measure the nearly full 3D electron velocity distribution function in every 800 milliseconds, and 3) a flux-gate magnetometer to make a vector measurement in 30 milliseconds.

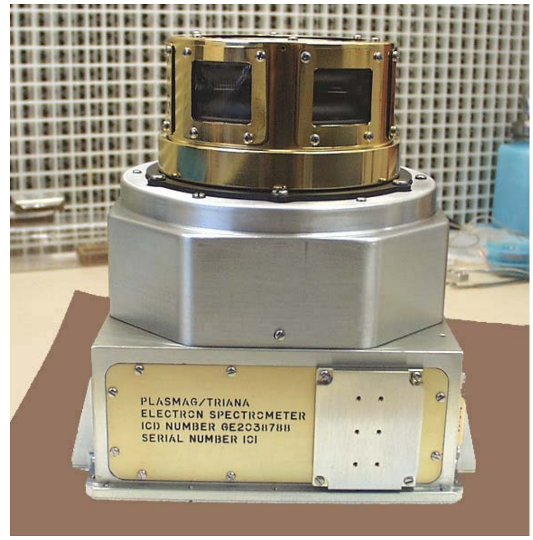

Figure 3. The DSCOVR electron tophat electrostatic analyzer.

The Faraday Cup is particularly suited for precise solar wind measurements on a three-axis stabilized spacecraft because of its large field of view (± 30°). The use of three separate collectors allows the full range of the solar wind deflections (~ ± 15° in all directions) to be accommodated, while still allowing a reduced 3D velocity distribution function to be collected. Thus whole distribution function remains in the field of view at all times so that accurate and high time resolution solar wind moments (density, velocity and temperature) can be computed.

The tophat electrostatic analyzer (Figure 3) will make measurements of the electron distribution function between 5 eV and 2 keV in a time as short as 800 milliseconds. The instrument has a set of six anodes distributed uniformly in azimuth, each with a field of view of 50° x 7° in azimuth and elevation. The coverage in elevation is accomplished by varying the potential of external deflection plates resulting in 15 different elevation angles between +60° and -60° above and below the plane of the anodes. Thus the instrument, sitting at the tip of a 7 m boom, has almost complete 4π sr field of view. This allows the rapid determination of electron temperature anisotropies and any variation in the electron *strahl* component.

Completing the PlasMag instrument package is a standard flux-gate vector magnetometer also sitting on the spacecraft instrument boom. The magnetometer has a sensitivity level of better than 0.1 nT and a native data collection rate of 100 vectors per second, though only every fourth vector is going to be telemetered to Earth.

The combined PlasMag instrument suite will provide all the required measurements identified to accomplish the science objectives outlined at the beginning of this paper.

3. MISSION HISTORY AND ASSOCIATED NASA COST ESTIMATE

In 1998, then Vice-President Al Gore proposed a mission to the earth-sun first Lagrange point (L1) to observe Earth as a planet. This mission was named Triana after the lookout on Christopher Columbus's fleet who was reported to be the first person to see the new world. The mission development proceeded for 21 months and spent an estimated $249M (in FY07$) before being de-manifested from the Space Shuttle. Then the spacecraft was placed in a state of "Stable Suspension" starting in November of 2001 and it was renamed the Deep Space Climate Observatory. (DSCOVR). In 2008, NASA was requested by the United States Air Force (USAF) and the National Oceanic and Atmospheric Administration (NOAA) to complete a study of refurbishing DSCOVR for a launch in 2012. While there had been several previous studies quite similar in nature, this study was unique in that it included funding to remove DSCOVR from storage and perform a power-on test to assess the current status of the observatory. These tests were completed by May 2009 and a refurbishing cost estimate was provided to NOAA. Currently, Congressional NOAA funding is pending to pay for the refurbishing of DSCOVR and a tentative USAF launch vehicle is provided for a December, 2012 launch date.

The NOAA paid for DSCOVR mission is an exclusively real-time space weather monitoring undertaking and, therefore, the NOAA budget includes only elements that are necessary to produce the low cadence space weather measurements. While the DSCOVR spacecraft space science instruments have only a single mode of operation, and therefore, the complete high time resolution data telemetry has to be transmitted to Earth, the NOAA DSCOVR science center is planning to produce only ~ 1 minute cadence solar wind data products. It would fall to NASA to provide the necessary funding to produce the unique, high time resolution data products. Based on the current, highly optimized Wind spacecraft instrument data production experience, the high cadence data products from the three DSCOVR PlasMag instruments would require a yearly NASA funding level of ~ $1M.

4. EVALUATION CRITERIA

Identification as a high priority or requirement in previous studies or roadmaps. An L1 solar wind monitoring mission is explicitly identified by the 2003 Decadal Survey (*The Sun to Earth – and Beyond: A Decadal Research Strategy in Solar and Space Physics*") as a small mission. The Survey moreover discusses the importance of continued L1 space weather predictions also echoed by the 2009 NASA Heliophysics Roadmap. This later document calls for a multi-agency effort to accomplish this goal. The DSCOVR mission, supported by NASA, NOAA and the USAF would fit this objective well.

Makes a significant contribution to more than one of the panel themes. The DSCOVR high time resolution solar wind measurements will address both solar/heliospheric (solar wind acceleration, IP shock structure) and solar wind/magnetosphere interactions science objectives. Also, since DSCOVR is designed to be a real time space weather monitor, it directly contributes to the research to operations theme.

Contributes to important scientific questions facing solar and space physics today. The DSCOVR high time resolution solar wind measurements will directly allow the investigation of solar wind heating, evolution and transient structures.

Contributes to applications and/or policy making. The DSCOVR solar wind proton and magnetic field measurements would be immediately used by NOAA operational space weather forecasting. The operational value of high cadence measurements and electron distribution functions are still a matter of scientific research. But DSCOVR will provide the ideal test case for the transition of these new measurements into operational space weather forecasting.

Complements other observational systems or programs available. A 20131 launch of DSCOVR would provide an ideal overlap with the current ACE and Wind missions. This would not only allow intercalibration of similar instruments, but facilitate multi-point studies.

Is affordable. The cost of obtaining high time resolution solar wind measurements from DSCOVR is eminently cost effective as the brunt of the mission cost is on NOAA and the USAF. For a nominal investment, NASA would obtain a scientifically valuable data set that normally would require the investment of a complete mission. This is a unique opportunity.

Technical readiness. The DSCOVR spacecraft is already completely built, and once the NOAA appropriation is approved, it will take only 18 months to refurbish the spacecraft and its instruments for a USAF launch.

Fits with other national and international plans and activities. The DSCOVR mission fits readily into the US National Space Weather Program.

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Dayside Aurora and Auroral Conjugacy

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Overview

This white paper discusses the scientific significance of dayside and conjugate auroras. The dayside aurora and its variation have less ambiguity in the connection to their cause. Examples of such advantages are: 1) the timing of the shock-aurora trigger (i.e., the touchdown time of an interplanetary shock on the subsolar magnetopause) can be as accurate as from few seconds to few minutes; 2) the shock-aurora speed in the ionosphere can be compared with the shock speed in the solar wind. These features provide a unique opportunity to test the existing theories of auroral dynamics, and to establish one-to-one correlations between the auroral forms and particle precipitation mechanisms. Measurements of dayside and conjugate auroras can be achieved by conducting balloon campaigns in the Antarctica and by coordinating the balloon observations with simultaneous Arctic ground-based auroral imaging.

1. Science Background

The aurora provides a map of magnetospheric structure and dynamics and thus auroral images provide rich information about the global magnetosphere that cannot be obtained from in-situ observations alone. The physics of the dayside aurora is different in many ways from that of the nightside aurora because of dayside-nightside asymmetries of the magnetosphere and the ionosphere due to the presence of the solar wind and solar photon ionization. The insight provided by studying the dayside aurora is critical to determining the coupling between variability in the solar wind and the resulting geospace response.

One salient dayside auroral phenomenon occurs when interplanetary shocks or sudden increases in the solar wind ram pressure impinge on the subsolar magnetopause. As a consequence, the magnetospheric compression and magnetic reconnection are enhanced in the local noon sector. Auroras in the dayside auroral ionosphere from the oval to ~65° MLat light up within seconds to few minutes indicating causes of the aurora in the outer magnetosphere and/or on the magnetopause ~10 R_E away from the ionosphere (Craven et al., 1986; Sandhalt et al., 1994; Spann et al., 1998; Zhou and Tsurutani 1999; Vorobjev et al., 2001; Liou et al, 2002; Zhang et al., 2002; Hubert et al., 2003; Meurant et al., 2003,2004; Zhou et al., 2003; Fuselier et al., 2004; Zhou et al., 2009). The auroras then propagate antisunward along the oval at very high ionospheric speeds of ~6-11 km/s that match the corresponding shock speed in the solar wind. The aurora is found to be caused by both the electron and proton precipitation. The auroral brightness is related not only to the variation in the solar wind, but also the plasma precondition in the dayside magnetosphere.

There have been speculations as to the causes of the aurora, such as magnetic reconnection, wave-particle interaction and magnetic shearing, etc. However, since there is a lack of observations of the small-scale dayside auroral structure, we have little understanding of a one-to-one correlation between auroral forms and the particle precipitation mechanism. For example, theoretically, a fast release of magnetic shear stresses could establish field-aligned potential drops and convert the differential magnetic energy into kinetic energy of auroral particles (Haerendel 2007; 2008). But the theory is not tested by auroral observations and it is unclear what would be the resultant auroral color (i.e., the electron characteristic energy), auroral form and their variations. Another example is that it has been a long-time belief that dayside red arcs are the manifestation of the magnetic reconnection on the magnetopause (e.g., Moen et al., 1998; Sandhalt et al., 1998a,b; Chaston et al., 2005). The red oxygen OI^{1}D emission layer is mainly at ~250 km altitude and caused by soft electrons with the characteristic energy of few hundred eV. However, a 1-D MHD model showed that Alfven-wave accelerated electrons possess energies up to few keV (Chaston et al., 2002). On the dayside magnetopause the kinetic Alfven wave is very likely generated by the magnetic reconnection (Chaston et al., 2005).

It has been a long-term challenge to image the aurora from the ground under sunlit conditions (e.g., Ree et al., 2000). This is mainly due to substantial contamination by sunlight and the limited land area available for installing imagers near the auroral zone in both hemispheres. While ultra-violet remote sensing from space can measure dayside aurora, it does not resolve small-scale auroral structures and is contaminated by UV airglow. Consequently, we have little knowledge of dayside auroral small-scale structures (i.e., auroral forms), their variations, and their coupling to conjugate aurora. As a result, there are important unanswered questions regarding the coupling between the variable solar wind and the dayside magnetosphere and ionosphere and also questions about the basic phenomenology of small-scale dayside auroral structures.

2. Scientific Questions

These questions include:

1). What are the auroral particle precipitation mechanisms? The advantage of studying dayside auroras is that there is less ambiguity in identifying the solar wind and magnetospheric causes of the auroral particle precipitation. The touchdown time of an interplanetary shock on the subsolar magnetopause can be accurately identified up to few seconds – few minutes; the auroral speed in the ionosphere matches that in the solar wind. These characteristics are unique opportunity to test various kinds of auroral mechanisms.

2). How do the dayside magnetosphere and ionosphere respond to solar wind variations in terms of auroral forms? (e.g. diffuse auroral patches and their expansion, auroral arcs/beams and their motion, the auroral response to abrupt solar wind pressure changes, jumps in IMF direction or stable but intense IMF such as in magnetic clouds.)

3). Are auroras (e.g., those seen during substorms, geomagnetic storms, and magnetospheric compression) hemispherically symmetric? The question covers the symmetry from small-scale structures (e.g., Sato et al., 1998) to global dynamics (e.g., Ostgaard et al., 2004; Laundal and Ostgaard, 2009). The answer can test many of current models and our understanding of geomagnetic disturbances. For example, do substorm onsets start in the auroral ionosphere (Kan and Sun, 1996) or in the magnetotail (Lui, 1991a,b; Baker et al., 2002)? The onset auroras in the two hemispheres are not necessarily conjugate for onsets in the ionosphere, but should be conjugate for those in the tail.

4). What signatures in conjugate dayside aurora can be used to diagnose reconnection and the response of the dayside magnetopause to IMF variations? What does this tell us about particle acceleration, magnetopause reconnection rates, and coupling of energy, mass and momentum from the solar wind?

5). What are the differences in the auroral emissions in sunlight and darkness? Are there unique signatures in the sunlight and what causes them? The answers will address the ionospheric conductivity effect and how it couples with the dayside and nightside magnetospheric dynamics.

6). What are the differences in auroral forms in dayside (~06-12-18 MLT) and nightside ionosphere (~08-00-16 MLT)? This question addresses the difference of the solar wind-magnetosphere-ionosphere interaction in the dayside and nightside geospace areas.

Identifying dayside auroral forms actually has broader applications beyond the above questions. It has been confirmed by the FAST and Cluster observations that ion conics occur along with the broadband VLF waves where soft electrons (with energy less than 1 keV) are seen to be highly field-aligned with the magnetic field (e.g., Chaston et al., 2005). Red auroral arcs are expected at the ionospheric footprints of the field lines. This connection between the red arcs and the ion conics implies that the red arc can be an indication of the oxygen ion outflow that is considered a very important, if not the most, ionospheric source of the ring current energetic ions. Could this indication only valid in the dayside/cusp or change case by case? Furthermore, since the dayside red arcs are caused by the magnetic reconnection (e.g., Chaston et al., 2005), there is a strong likelihood of the reconnection being the very responsibility of the oxygen ion outflow. This speculation is consistent with Strangeway et al.'s flow chart for the generation of ionospheric outflows (Strangeway et al., 2005) and is consistent with the fact that geomagnetic storms develop only when there is a long lasting southward IMF.

3. Technical Approach and the Feasibility

To answer such questions, the basic requirement is to image the aurora in relatively close distance (so auroral forms can be determined) in sunlight. If such measurements can be achieved, conjugate auroral images can be obtained by combining auroral images taken in sunlight (local summer) from Antarctic balloons with simultaneous Arctic ground-based auroral images taken in darkness (local winter). Thus, the science questions lead to a technical challenge, i.e., how can we image aurora under sunlight? Seeking a feasible method has been a continuing effort (Chakrabarti, 1998; Rees et al., 2000; Pallamraju et al., 2004), which deserves a solution because of the science significance discussed above.

Atmospheric models predict that sky brightness decreases with increasing altitude and wavelength (Anderson et al., 1999; Liou, 2002). Based on these models and test observations, Zhou et al. (2007, 2008) have confirmed that the N_2^+ Meinel line emissions (~1100 nm), which gives the best signal noise ratio (SNR) in near-infrared, can be measured in sunlight at typical balloon altitudes (>35km) where signal to background ratios are adequate. Using a JPL built near-infrared (NIR) InGaAs camera (with a small focal plane array of 320 x 256 and a small FOV of 9º), the Meinel auroral emissions were detected during twilight when the sky brightness was similar to that of 35-40 km altitude during the highest solar elevation in the Antarctica.

Some of the images are shown in Figure 1. The aurora was detected on April 13, 2005 during evening twilight when the solar zenith angle, SZA, was ~96° (i.e., the sun was ~6° below the horizon). Corresponding AL was about -400 nT implying a medium level of auroral intensity. This test result confirmed the feasibility of measuring sunlit auroras from balloon. When the measurements in the Antarctica are coordinated with the existing ground-based all-sky imagers, conjugate auroras can be obtained.

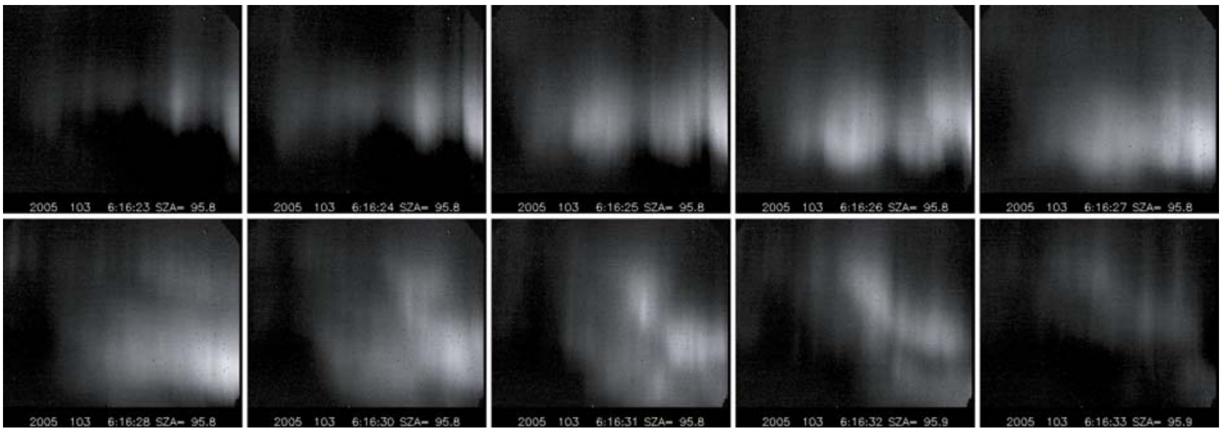

Fig. 1. Auroras detected by the JPL InGaAs NIR camera from Poker Flat, Alaska. Images are shown in one second cadence chronologically from left to right, then down to the second row. Without applying any filter, the images were taken in evening twilight from 2116:23 to 2116:33 LT on April 13, 2005 when SZA was ~96°. Each image has had a sky background subtracted that was calculated from 40 images around the time of the image (Zhou et al., 2007, 2008). The sky background is mainly contributed by the OH airglow in 1400-1700 nm (Remick et al., 2001). Detailed discussions of the sky intensity can be found in Zhou et al. (2007, 2008).

Comparing to space mission, balloon flight for auroral observations is very cost effective with a total cost only ~$2M including the balloon flight and the NIR camera system development. The JPL NIR InGaAs camera technology has a TRL 5-6 and possesses much better quality than commercial NIR cameras that only function well under high frame rate of ~100/s or higher. With current NASA balloon technology, flying at 35-40 km altitudes with a 1000 kg payload is routine.

The NASA balloon altitude record is ~50 km with ~200 kg payload. Driven by the Antarctic circumpolar winds, a balloon can maintain a trajectory around the geographic pole over several weeks. (Such an example of the balloon trajectory relative to the oval and the NIR camera's field-of-view is shown in Zhou et al., 2007.) The NIR camera system requires less than 10 kg weight and consumes ~30 W, which are suitable for the balloon flight and even a balloon piggyback flight.

4. Concluding Remarks

The 24th solar cycle started its ascending phase recently. Increasing solar and solar wind activity will more frequently light up intense auroral bursts. The Antarctic auroral campaign and its leverage with the ground-based all-sky imager arrays and with the Cluster and THEMIS satellite constellation will provide a unique opportunity for dayside and conjugate auroral investigations. (Note there certainly are opportunities to measure the nightside aurora in both hemispheres during a conjugate auroral campaign.) A broader coordination and collaboration with observations of riometer, X-ray, SuperDARN and other ionospheric measurements as well as theory/modeling will be strongly encouraged.

We highly recommend that the communities interested in the solar wind-magnetosphere-ionosphere interaction, high-latitude ionosphere, auroral dynamics, auroral conjugacy, auroral morphology and its magnetospheric causes, and auroral particle acceleration theory be given the opportunity to work jointly on measuring the dayside and conjugate aurora and on the auroral investigation.

The primary benefits of this task include: 1) an insight into the dayside geospace response to the varying solar wind; 2) one-to-one correlations between the auroral form and particle precipitation mechanism. Such correlations are helpful references for the nightside auroral activity; 3) the auroral conjugacy during the dayside reconnection, magnetosphere compression and magnetic shearing as well as during nightside auroral substorms; 4) a test of existing storm and substorm models and speculations; 5) a complementary method (that employs NIR camera for auroral emissions at ~1100 nm) to traditional visible and UV auroral remote sensing. Note that the characteristic energy of precipitated electrons alters with the auroral wavelength; and 6) a more complete knowledge of auroral micro-scale signatures along the global auroral zone.

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The Need for Explicit Basic and Applied Research Funding

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Recommendation:
The Decadal Survey Committee should advocate for distinct lines of funding by the U.S. civilian agencies for: 1. basic space physics research and 2. the development of space weather applications, maintaining distinct requirements for both. Under the current paradigm guiding research funding today, namely to favor research with societal benefit, neither basic research nor applications with value to society are being supported optimally.

Discussion:
Our Nation needs separate and explicit lines of funding for basic space physics research and for space weather applications. Because of the disparate nature of both the scientific effort and the time frames over which outcomes are expected for basic research and the development of applications, both activities suffer when funded under a single umbrella. Basic physics research is suffering from a perceived pressure on scientists to justify research in terms of space weather applications, and space weather applications with demonstrated utility are not being developed in a timely manner. Of course there is substantial overlap between basic research and applications, but there are important research and application areas in need of support that reside outside the overlap and consequently are being neglected.

Following the National Academy report on societal and economic impacts of space weather (2008), a number of government agencies around the world (including the Federal Emergency Management Agency and the Department of Homeland Security in the U.S.) have begun to take the threat of space weather on our electric power and communication/navigation infrastructures seriously. As our community has been saying since the inception of the U.S. National Space Weather Program, there are important national needs that must be met, including the dramatic improvement of space weather forecasts and services.

With a few exceptions, models that provide specific space weather forecasts have improved little over the past decade. More importantly, it has not been demonstrated that the improvements that have been made are sufficient to provide value to users who need forecasts and services, such as the electric power and navigation industries. While new knowledge has been gained from the excellent missions and research supported over the past decade, this knowledge has not been translated into capabilities with societal value.

This issue is not part of the often-described research-to-operations challenge; it precedes it. Given the lack of models with proven value, the U.S. space weather effort is not yet to the point in its development where the transition of research models to operations is the dominant issue. We must first develop forecast models and demonstrate their value to society before expense to employ the capabilities in operations can be justified.

Conducting basic space physics research and developing space weather applications have key differences, both in terms of the desired outcome and the time frame over which an outcome will be achieved. Basic space physics research must be conducted with the goal of expanding knowledge, not creating something. The more our research is guided by a need to enable space weather capabilities, the less support there may be for basic research with unanticipated benefits. This sentiment was expressed at a recent meeting of the Decadal Survey Theory and Modeling Working Group (October 14-15, Boulder, CO). It was suggested that the recent emphasis on space weather has had a negative impact on basic space physics research. The perception that space physics research should have an identifiable tie to societal benefits may inhibit scientists from submitting proposals on basic research topics, and it may be detrimental to their proposals being supported. Interestingly, it was also pointed out at this meeting in a presentation by a different scientist that in spite of the focus of funding on space weather, few models today are capable of accurate forecasts. This combination of views from prominent scientists illustrates the gaps caused at both ends of the spectrum by our current approach to research funding: basic research funding has become difficult to obtain, and our stated goal of accurate forecast capabilities is not being achieved.

Just as basic research must be supported, research is also needed to create high-value applications that will address our near-term space weather needs. This effort is not engineering, but rather it involves focused scientific research to translate existing knowledge into the best possible applications. Similar to the parameterization of sub-grid-scale physics in today’s weather models, sophisticated techniques need to be developed to optimize our data and models for space weather forecasts.

Unlike basic research, space weather research must be outcome-based with near-term goals. It has been demonstrated over the past decade that improved forecasting capabilities do not result automatically from research targeted toward space weather topics. NASA’s Living With a Star Program and NSF’s Space Weather funding are the civilian programs closest to supporting the development of space weather applications, and they have enabled excellent research on the science underlying space weather. These programs do not directly support the development of applications, but rather support the acquisition of knowledge needed for the eventual development of space weather applications. The fact that few forecast models with demonstrated societal value have been developed over the past decade indicates that while the acquisition of new knowledge is necessary for improved applications, it is not sufficient for the applications to be developed. Unless explicit funding is applied with clear requirements for near-term outcomes, applications with predictive value to mitigate space weather impacts will not be developed in a timely manner. We need targeted innovations and improvements in our capabilities to occur over the next three to five years, not in 10 to 20 years.

We must recognize that although there is overlap in knowledge content, the development of a basic physics understanding requires separate funding and distinct goals from the development of space weather applications. Funding for applications must be outcome based. The emphasis must be on near-term solutions to key problems and on the quantification of our capabilities and their limitations. Our forecast capabilities have not improved dramatically over the past decade, and they will not improve dramatically over the next decade unless it is made an explicit priority of dedicated funding. Our Nation needs explicit funding both for basic space physics research and for space weather forecasting.

A White Paper advocating a *Heliophysics Theory Mission*

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1. Introduction

Theory and modeling, together with observations are the foundations of a sound, balanced scientific program in any discipline. The past few decades have witnessed a shift from a strongly exploratory and discovery-driven science to a more mature explanatory science. With its maturing, solar and space physics places increasing demands on theory. Theory provides a meaningful context for basic space physics observations, often revealing that seemingly disparate observed phenomena correspond to the same physical processes in a system(s). Critically, besides organizing and understanding observations, theory drives the prediction of new or unexpected important phenomena that in turn drive new missions.

Some 34 years ago it was realized that, within what was then called the Space Physics Division of NASA, theory and modeling was not adequately funded. At that time the Colgate Committee was formed. It found that, compared to peer disciplines such as fusion plasmas, space physics theory and modeling was significantly under-supported. The committee recommended that theory funding be increased and attention be given to the encouragement of critical-size theory groups. This recommendation led directly to the creation of the Space Physics Theory Program and indirectly raised the general awareness of the importance of a balanced program. This program still exists as the Heliophysics Theory Program, but at a significantly reduced fraction of the overall budget. This program has been an important factor in the significant progress made in the area of Heliophysics science of the past few decades, but the number of proposals supported now numbers 9 with a typical grant size of some $400k or less per year. This has decreased from 11 or 12 funded proposals just 20 years ago, and these were funded at levels that were comparable to today's (i.e., ~$400k in 1990 dollars)! There has therefore been a considerable erosion in both the number of theory groups supported in the US and in the level of individual support. With the reduction in the theory program, most theory is now being funded through guest investigator programs associated with missions or through the SR&T program. Unfortunately, the level of these programs is also being reduced, to the point that the last GI program was completely cancelled. The deleterious effect of the erosion in theory support can scarcely be over-estimated, especially in academic environments where it is now almost impossible to develop a major spacecraft or experimental program that can sometimes indirectly support the development of theory.

In significant measure, this erosion of theory and modeling funding appears to be the result of significant budget constraints combined with Mission cost growth. With respect to the latter, there appear to be several factors at work. Proposed budgets for a mission may not always reflect accurately the real costs – this may be due to overly aggressive or optimistic budgeting to ensure the selection of an instrument or mission, or it may be due to the shifting of the mission schedule and dates, or unexpected development costs, etc. NASA has frequently responded by adding further support to the mission (or perhaps de-scoping the mission, but often still with an increased budget), and the increase in mission funding has all too often resulted in a corresponding decrease in the level of support for theory and modeling related programs.

The purpose of this white paper is two-fold. 1) We recommend that theory and modeling be funded at a significantly enhanced level that would allow sizable teams of researchers to pursue major science projects using a combination of theory, modeling, and data analysis. We suggest that an individual grant could total as much as $1M/year, and that as many as 10 groups should be supported. 2) We recommend that the theory program be given the status of a Mission and be similarly protected against the vagaries of NASA funding, particularly in maintaining the level of funding and adjusting for inflationary increases.

2. Current state of Theory and Modeling

The Colgate report listed 6 specific problem areas in basic theory as important for the progress of Space Physics:

(1) Magnetic-field reconnection
(2) Interaction of turbulence with magnetic fields
(3) Behavior of large-scale flows and their interactions
(4) Acceleration of energetic particles
(5) Particle confinement and transport
(6) Collisionless shocks.

Although this list was compiled some 34 years ago, it is remarkably applicable to the present time. Significant progress has been made.

We now have a significantly improved understanding of each of the problems listed, due to more and better observations allied with theoretical and modeling advances, but in none of them can we claim to have achieved a more-or-less definitive understanding of the problem. Of course, the richness of each of these problems has spawned both increased understanding in related fields and new fields of inquiry.

Some case studies provide an interesting perspective on the development of theory, the associated modeling and simulations, and the role of data analysis. One example, a subset of the collisionless shock example, illustrates both our increasing understanding and the further fundamental questions that are opened up by theory.

<u>Collisionless Shocks</u> Our current understanding of perpendicular shocks is rightfully regarded as one of the major achievements of modern collisionless nonlinear plasma physics. A perpendicular shock wave has the upstream magnetic field aligned perpendicular to the shock normal. Deviations up to nearly 45^0 for the magnetic field from the shock normal are described as quasi-perpendicular, and a clear physical picture can be drawn since reflected ions will gyrate back to the shock front in this case. Nearly perpendicular shocks have received considerable

attention because of their relatively clean, laminar appearance in the time series data. The particle gyromotion in the quasi-perpendicular magnetic field acts to prevent particles behaving excessively diffusively (i.e., the particles tend to be bound together), thereby simplifying the collisionless processes responsible for thermalization of the plasma, and the injection and acceleration of energetic non-thermal particles. Despite much effort, key questions remained unanswered or open to interpretation, and prior to Cluster, single, and dual, spacecraft studies were unable to place quantitative limits on the spatial scales, or address non-stationarity of the overall shock transition. By taking advantage of the sharp, quasi-perpendicular shock transitions and four spacecraft techniques, Cluster studies can probe internal shock scales and physics, including energetic particle origin, of the Earth's quasi-perpendicular bow shock. This has led to a resurgence in theoretical studies of the perpendicular shock, with many of the formerly accepted assumptions now being questioned. For example, the role of dimensionality in kinetic simulations and the importance of the electron/ion mass ratio are now recognized as introducing different behavior in the simulations depending on the assumptions. In all of this, the role of magnetic-field-line mixing must also be considered.

The capacity for the Voyager Interstellar Mission to surprise remains undiminished, with the recent crossing of the heliospheric termination shock (HTS) by the Voyager 2 spacecraft. With a working plasma instrument, the Voyager 2 observations revealed a quasi-perpendicular heliospheric termination shock that appears to be considerably different in character from quasi-perpendicular shocks observed in the inner heliosphere. The Voyager 2 observations suggest the possibility of a broad structure, or a velocity slowdown before the shock, possibly considerable fine-scale structure, many partial termination shock crossings, very little heating of the solar wind protons, to the extent that the downstream flow appears not to be subsonic, and a density spike appears to be present. These results suggest that the heliospheric termination shock is unlike any heliospheric shock observed elsewhere. Nonetheless, the observations were not entirely unexpected theoretically. It had been argued that the primary dissipation mechanism at a quasi-perpendicular heliospheric termination shock would be reflected pickup ions, and that the solar wind ions would be heated very little. This basic concept appears to have been borne out by the Voyager 2 observations.

Thus, theory appears to be making headway in our basic understanding of quasi-perpendicular shock physics but fundamental questions remain unresolved, and have not been clarified observationally, in part because without an accepted theoretical structure, it is difficult to know what we should be looking for. For example, even the question of the scale length over which changes in the electric field occur and its relation to the scale size over which changes in the magnetic field occur is unclear theoretically and observationally.

<u>Transport and acceleration of energetic particles</u> The acceleration of energetic particles and cosmic rays is thought by many to be caused by shock waves. Perpendicular shocks, such as much of the termination shock, are efficient and fast accelerators. With the crossings of the termination shock, it has become clear that the early theoretical models were too simple. The energetic particles did not behave as expected. In response, a number of approaches have been suggested. Non-shock acceleration mechanisms such as reconnection and statistical acceleration have been resurrected and the effects of pre-existing turbulence have been examined. Thus, theory drove certain expectations of particle acceleration at the heliospheric termination shock,

some of which were met and others not by the Voyager observations. Clearly, a major theory effort is now needed to address these recent developments.

All of these acceleration issues require an increased understanding of particle transport, both in formulating the theories and in interpreting spacecraft observations which are most-often remote from the acceleration site. These theoretical and modeling issues are of basic importance throughout physics, ranging from thermonuclear plasmas to supernova blast waves. Thus, increased knowledge here will have broad impact.

<u>Magnetohydrodynamic turbulence in the solar wind</u> Magnetohydrodynamic (MHD) turbulence is characterized by nonlinear interactions among fluctuations of the magnetic field and flow velocity over a range of spatial and temporal scales. It plays an important role in plasma heating, the transport of energetic particles, such as galactic and anomalous cosmic rays, and radiative transfer and is ubiquitous in the solar and interplanetary plasma. The solar wind exhibits turbulent behavior, as can be observed from in situ data. Solar wind fluctuations are observed over spatial scales that range from many AUs to electron kinetic scales. These observations have stimulated an ongoing effort to develop theoretical treatments of MHD turbulence. Large-scale fluctuations can be described by fluid models, but the smaller than proton scales requires Hall MHD or a kinetic description. The coupling of large-scale and kinetic-scale processes in the solar wind is mediated by the turbulence. Energy is transferred from large-scales to small-scales through turbulent fluctuations, including eddies and waves, that interact. The cascade is eventually halted by kinetic processes and heats the plasma. With an explicitly turbulence-based model that includes appropriate source terms, the radial evolution of turbulence intensity and the temperature of the plasma has been computed successfully from 1 to > 50 AU.

Solar wind turbulence remains incompletely understood despite considerable progress in the last 20 years. It is an important problem since turbulence mediates the complex dynamical couplings between large and small scales, slow fluid motions and fast kinetic processes, and low energy and high energy charged particles. Numerous important theoretical problems remain unresolved, ranging from compressible effects, passive scalar transport, the dimensionality and symmetries of interplanetary turbulence, etc.

While the Colgate Report list of fundamental plasma physics problems remains comprehensive, at least one additional area of fundamental research has assumed particular importance for solar and interplanetary plasmas. In the examples described above, a common element was the interaction of the heliosphere with interstellar material, especially the neutral gas (hydrogen). This took the form of a new shock dissipation mechanism based on interstellar pick-up ions, the acceleration of anomalous cosmic rays, and even the heating of the solar wind by pick-up ions providing the energy (through a resonant instability associated with pick-up) that cascades to kinetic scales and heats the solar wind. A more detailed example related to the formation of the "hydrogen wall" is given below. Thus, to the Colgate Report list, we would add the additional fundamental problem of ***Partially-Ionized Plasmas***.

<u>Structure of the heliosphere</u> The physics of the outer heliosphere and the large-scale structure of the heliosphere is determined fundamentally by its interaction with the partially ionized local interstellar medium (LISM). To illustrate, an important development in outer-heliospheric

research was the prediction and discovery of the "hydrogen wall." Theoretical models predict that the partially ionized LISM and the solar wind are separated by a complex set of plasma and neutral-atom boundaries, of which the termination shock has now been observed by the Voyager spacecraft. A specific theoretical prediction of the models is that a wall of interstellar neutral hydrogen should exist in the upstream region owing to the relative motion of the heliosphere and the LISM. This hydrogen wall is predicted to have a number density slightly more than twice the interstellar density, to be hotter than interstellar hydrogen, and to be some 100 AU wide. The physical reason for the hydrogen wall is the deceleration and diversion of the interstellar plasma flow about the heliosphere leading, through charge-exchange coupling, to a pile-up and heating of interstellar neutral hydrogen. The result is the formation of a giant wall, which acts to filter neutral hydrogen as it enters the heliosphere. Confirmation of the hydrogen wall's existence was not expected for decades, but a serendipitous convergence of predictive theoretical modeling, observations to place limits on the cosmological deuterium/hydrogen ratio, and a multi-disciplinary investigation spanning space physics and astrophysics led to the detection of the hydrogen! This was the first of the boundaries separating the solar wind and the LISM to be discovered, and it offers a glimpse into the global structure of the three-dimensional heliosphere.

The research leading to the discovery of the hydrogen wall is an excellent example of theory driving the frontiers of space science and motivating the development of new observational techniques and methodology to complement traditional space physics tools.

3. *Theory and Modeling*

It is important to emphasize that the terms theory and modeling are not synonymous, and th must both be present in a balanced program. We view theory as the extension of our basic knowledge of phenomena. Theory attempts to find new physical descriptions of poorly understood phenomena. Modeling, on the other hand, involves the implementation of theory to complicated, realistic situations and scenarios. This often involves considerable investment in computer hardware and software. The end results are quantitative predications that can be directly compared to observations. An illustrative example is the creation of a synthesized time dependence of the predicted magnetic field or energetic particles along a real spacecraft trajectory to compare with an observed timeline.

Noting this distinction between theory and modeling allows us to consider several essential elements that a theory program needs to address.

<u>Formulation of theoretical models</u> In recognizing that multiple scales, regions, processes, and plasma populations are intrinsic to the challenging space physics problems of today, the correct mathematical and physical formulation is critical. In this, there is no substitute for time-honored analytical approaches to theoretical developments in plasma physics, fluid dynamics, and applied mathematics. Progress on highly nonlinear, coupled plasma problems may be made using techniques that range from the relatively standard to nonlinear, low-order reductive approaches and statistical methods. Current agency funding programs are not adequate to even support these basic theoretical efforts, and unfortunately innovative and bold ideas, approaches, and techniques in proposed research are often not encouraged and rewarded. Computation is no substitute for the development of rigorous theories and well-conceived models. Basic theory must be regarded as a

critical component of the funding profile for either NASA or the NSF and a Mission-level perspective must be encouraged

Invariably, many of the problems listed in the “extended” Colgate Report list impose significant computational demands in terms of CPU power and the concomitant development of sophisticated and efficient codes. Two challenges face the community. The first is to further develop existing codes and algorithms, such as three-dimensional MHD codes that incorporate adaptive mesh refinement, for example, or three-dimensional hybrid codes with improved electron/ion mass ratios or improved codes for data exploration. These problems do not demand the inclusion of new physics but demand instead substantial progress in current research areas. The second challenge lies in developing and implementing new computational approaches for both model solving/simulation and data exploration that exploit advances made by numerical mathematicians, statisticians, and computer scientists.

The coupling of different physical processes, scales, and regimes and the self-consistent incorporation of multiple scales, physical processes, and distinct regions into models will be the main challenge to theorists and modelers in the coming decade, demanding the formulation and development of sophisticated models and theory, the development of new and innovative algorithms, access to sophisticated computational resources, and the opportunity to test model predictions and validate theories against existing and future observations. We know that theory will demand sophisticated new measurements, which will in turn drive and define new space and ground-based missions (in situ, multipoint, remote, etc.). A theory program must focus on the investigation of well-chosen, theoretical problems and the development of coupled global models. For major advances to be made in space physics, fundamental theoretical analysis, sophisticated computational tools, and state-of-the-art data analysis must all be coupled intimately under a single umbrella program. Theoreticians working with pen and paper, computational space physicists, and data analysts will be needed collectively to achieve the major advances expected of space physics. Only by creating and maintaining major groups of this sort can a strong and vital connection between basic science, computation, and observations be achieved.

A well-balanced discipline would be in a position to leverage more fully the remarkable observational possibilities to increase our understanding of our home in space.

4. *Recommendation and Implementation*

The above specific examples and issues document the real decrease in support of theory, both absolutely and relative to the missions. We therefore recommend that theory and modeling be protected from further erosion and be restored to the relative position it had in the aftermath of the Colgate report.

We propose the creation of a New Theory MISSION. What is needed for a successful Theory Program? The answers are rather simple:

- Long-term, stable funding;

• Synergistically interacting groups of students, postdoctoral associates, research scientists, and several university or institutional faculty who are able to integrate research and education at some level.

To guard theory and modeling from continuing erosion, we propose that a theory mission be created with a specific goal or goals and a specified time line, in analogy with a hardware mission. One possible scenario would involve selecting one of the issues discussed above as the target of the Mission. For example, one might select a 'Mission to Understand the Interaction of the Heliosphere with the Local Interstellar Medium", or perhaps 'The Sources of the Interplanetary Magnetic Field as a focus for a 5-year effort. Within such a mission concept, one would fund separate groups (in analogy to separate instruments), some to work on aspects of basic theory, others to develop models and simulations and perhaps others to work on the connections with observations.

Such a mission should NOT be funded at the expense of the usual SRT or GI programs.

In summary,
1) we recommend that theory and modeling be funded at a significantly enhanced level that would allow sizable teams of researchers to pursue major science projects using a combination of theory, modeling, and data analysis. We suggest that an individual grant could total as much as $1M/year, and that as many as 5-10 groups should be supported at any one time, for up to 5 years; and 2) we recommend that the theory program be given the status of a Mission and be similarly protected against the vagaries of NASA funding, particularly in maintaining the level of funding and adjusting for inflationary increases.