Recommendations for Education/Public Outreach (E/PO) Programs:
A White Paper Submitted for Consideration to the NRC Decadal Survey in Solar and Space Physics

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Importance of Education/Public Outreach (E/PO)

This white paper addresses the importance of Education/Public Outreach (E/PO) as a major contributing factor to workforce development in solar and space physics as well as in creating a scientifically literate American public.

Education/Public Outreach (E/PO) includes formal, informal and outreach programs, activities and resources. Formal education focuses on learning that takes place in a structured educational environment. This could include teacher workshops, curriculum development, or programs for students within a classroom at K-12, undergraduate or graduate levels. Informal education falls outside established school systems. This includes education that occurs in such settings as museums, planetaria or parks. Public Outreach encompasses accessible and relevant events and programs that reach out to the general public, often in a community setting.

E/PO efforts directly address NASA, NOAA and NSF strategic goals. All three agencies include statements in their strategic plans regarding their goals to strengthen the future workforce in science, technology, engineering and math (STEM) fields as well as raising the level of scientific literacy of the American public (NASA Heliophysics Roadmap Team, 2009; NOAA, 2009; NSF, 2006). E/PO efforts provide a means through which NASA, NOAA and NSF can achieve their goals of establishing a diverse, highly skilled and effective STEM workforce as well as a scientifically literate public that is better able to make informed decisions regarding scientific issues that affect society.

Collaboration between Scientists/Engineers/Technical Staff and Educators

It is important to acknowledge that Education is a specialized profession which involves its own body of research, theory and best practices. Within the larger field of Education, E/PO professionals have specialized expertise in collaborating with scientists, engineers and technical staff for the purpose of furthering workforce development and scientific literacy.

Within solar and space physics, the E/PO community has seen best practices emerge from the collaboration of research scientists, engineers and technical staff with educational experts. According to the findings put forth in *NASA's Elementary and Secondary Education Program: Review and Critique* (Quinn et al., 2008), "the primary strengths and resources that NASA brings to K-12 STEM education are its scientific discoveries, its technology and aeronautical developments, and its space exploration activities, as well as the scientists, engineers, and other technical staff that make up its workforce and the unique excitement generated by flight and space exploration."

This finding provides solid reasons for continuing the requirement that a percentage of NASA Science Mission Directorate (SMD) funds be allocated to education and public outreach related to SMD missions. This strategy capitalizes on NASA's primary strengths and resources by directly connecting educational endeavors to the science of NASA missions.

This collaborative model has the added benefit of achieving direct buy-in from scientists, engineers and technical staff regarding the importance of education outreach projects. Often scientists, engineers and technical staff do not prioritize educational outreach because it may distract from their research focus. However, when E/PO is embedded within scientific research or missions, these professionals tend to become more active participants in the educational outreach. This benefits the participants in the E/PO program, whether they are K-12 students, undergraduate students or the general public, because the participants have access to the scientists, engineers and technical staff's expertise and current research. Such a model brings the excitement of missions and scientific research to the targeted educational audience. The enthusiasm generated here can lead participants to pursue additional opportunities in the STEM workforce pipeline.

One example of a NASA SMD E/PO program that directly led students to choose to pursue undergraduate science education was the THEMIS (Time History of Events and Macroscale Interactions during Substorms) E/PO program (Peticolas, 2009). In this program, students were engaged in a magnetometer program shared the positive impact of being connected to current NASA mission with the teachers who were directly involved in the THEMIS program (Walker, 2009, pg. 25-26).

Recommendation:

- *Continue the requirement that a percentage of NASA Science Mission Directorate (SMD) funds be allocated to mission-related education and public outreach.*

<u>Extending the Reach of E/PO Programs</u>

In considering the impact of any Education/Public Outreach program, there is often a dichotomy between numbers of people reached and the depth of each person's experience. Frequently, there is an inverse correlation between the first and the latter. That is to say, E/PO programs that seek to reach large numbers of people often do so by providing a relatively short experience for those people. For example, a booth at a community fair may reach large numbers of people who engage in activities for only a few minutes. In this scenario, the goal of the program would likely be to raise awareness or inspire the participant. On the opposite end of the spectrum, some E/PO programs may work with relatively few participants but the experience provided to them is extremely deep. An example of this might be a mentorship program in which a few students work closely with a scientist over the course of a year.

Both these types of programs have value but it would be worthwhile to design programs that seek to maximize the program's reach without sacrificing depth of experience. One strategy for doing this is a "train-the-trainers" program model. In these types of programs, E/PO specialists and scientists train educators and volunteers in science content and dissemination strategies, after which the trained participants share what they have learned with other teachers, students and the general public. This model is successful because it extends the numbers of people affected and because the trainers become very powerful spokespeople for the science. This model also maximizes resources and ensures a good return on investment.

The NASA-funded Heliophysics Educator Ambassador (HEA) Program is an excellent example of this best practice (Peticolas et al., 2010). The goal of the HEA Program is to develop the capacity and provide the opportunity to train other teachers on NASA Heliophysics science and educational resources. Master teachers attend week-long training sessions and receive follow-up support for several years via teleconference calls and other electronic communications. These Heliophysics Educator Ambassadors then implement lesson plans based on NASA Heliophysics education resources in their own classrooms and also train other teachers at local and regional professional development conferences or meetings. The HEA Program develops well-qualified science teachers who use hands-on science experiments that connect science to real life. Such teachers, with their expertise and enthusiasm, are important contributing factors to students pursuing STEM (Levine et al., 2007).

The "train-the-trainers" model can also be used in informal education environments, as seen in the NASA-JPL Solar System Ambassadors program and Museum Alliance program. In the Solar System Ambassador program, volunteer Solar System Ambassadors attend teleconferences and receive educational resources related to NASA missions. The Solar System Ambassadors then conduct workshops, events and lectures in their home communities. In the Museum Alliance program, informal educators at museums, planetaria and science centers receive mission briefings and science information from NASA scientists, which they then use to educate the people who attend their institutions.

Recommendation:

- *Support existing "train the trainers" programs and initiate other kinds of "train the trainers" programs.*

In the case of NASA Senior Review missions, relatively small amounts of funding are set aside for mission-related E/PO efforts. One best practice for extending the reach of E/PO programs is to coordinate efforts across various divisions or missions within a funding agency. Such intra-agency collaboration leverages E/PO funds to achieve a greater impact than would otherwise be possible in isolation.

The Heliophysics Educator Ambassador (HEA) Program (Peticolas et al., 2010) also serves as an example of how an E/PO program can extend the reach of individual NASA missions through coordination of efforts within the funding agency. The HEA Program is supported by the THEMIS/ARTEMIS mission in collaboration with IBEX, AIM, RHESSI, TIMED, RBSP, MMS, STEREO and (previously by) Cluster. By combining E/PO funds from multiple missions, the Heliophysics Educator Ambassador Program is able to extend the reach of impact much further than any one of the individual mission funding sources could have done individually.

Recommendation:

- *Provide opportunities for intra-agency collaboration on Education/Public Outreach efforts.*

Increased Emphasis on Engaging Underrepresented Groups in STEM

NASA, NOAA and NSF state in their policies that they seek to increase the participation of underrepresented groups in STEM. Underrepresented groups typically include women and ethnic minorities, particularly Hispanics, African-Americans and Native Americans. Engaging underrepresented groups in STEM education is important because it has implications for STEM workforce diversity.

According to a National Science Foundation report (1994), in 1990, Hispanics, African-Americans and American Indians represented 19% of the total labor force but only 8% of the science and engineering labor force. In the case of Hispanic Americans, the US Census Bureau (2006) estimates that this population will triple by the year 2050. As the diversity of the American public continues to grow, the issue of underrepresentation becomes even more acute.

Similarly, in 1990, women made up 46% of the labor force in all occupations, but only 22% of the science and engineering labor force (NSF, 1994). Although strides have been made in engaging women professionally in astronomy, anecdotal observations suggest that the number of women involved in heliophysics lags behind. For those women who do pursue physics professionally, many report facing discrimination and negative attitudes about women in science (Ivie & Guo, 2006). Studies of young women of color in physics (Ong, 2005) provide recommendations that could be valuable in space physics (strongly tied to physics departments throughout the country) about how university departments should reform to promote more women and underrepresented minorities in science.

Recommendation:

- *Conduct research and use physics education research to identify best practices in engaging women and minorities in space science, then support and highlight programs and university departments that utilize such practices.*

A National Research Council report on learning science in informal environments summarizes research that shows how "scientific discourse, teaching, and learning are not culturally neutral" (NRC, 2009). Although the laws of science may be universal, the culture in which professional science takes place is not. The norms of science have largely developed out of western (North American and European-centric) cultures. Engaging in science typically requires an understanding of specialized language, western methods of conceptual organization and the ability to succeed within narrowly defined pedagogical practices.

One strategy for making science more accessible to some underrepresented minorities is to take an interdisciplinary approach to E/PO programs. This approach recognizes the science-related practices of cultural groups that have a holistic understanding of the earth and space environments. Rather than presenting science as something that is separate from human beings, this strategy emphasizes the interdependency of people and the natural world. Science is one way of many valid ways of understanding this connection.

Within heliophysics, this strategy could be employed by exploring the vibrant relationship between the Sun and Earth with a focus on cultural adaptations. For example, E/PO programs could engage participants in science by exploring the ways in which various cultures have and still do use the Sun (as calendars, for planting, etc.). For many people, the Sun-Earth connection is best understood as part of a holistic framework that explores the interrelationship of life on Earth with the Sun. Presenting the science content in this way makes it accessible to a larger audience by providing multiple ways of understanding the Sun-Earth relationship. Engaging with audiences within their culture can be incredibly meaningful to the participants as well as the E/PO partners.

Recommendation:

- *Provide funding support for interdisciplinary E/PO programs and resources including those which recognize that "all people engage in sophisticated learning shaped by the cultural and contextual conditions in which they live" (National Research Council, 2009).*

For many people, choosing which profession to pursue is a process that involves a series of decisions. This process typically begins in early childhood with activities that may seem inconsequential but turn out to have lasting effects. For example, one survey of 3400 individuals who had graduated with degrees in STEM disciplines showed that 59% first became interested in STEM topics in childhood (Russell et al., 2007). This may be especially true for girls. Research shows that parental encouragement of a child in science may be the single strongest social influence on girl's choices of science career choices (Campbell & Connolly, 1987). These findings suggest that E/PO programs that engage both young children and their parents in STEM education are of vital importance in the STEM workforce pipeline.

Recommendations:

- *Provide funding support for programs and resources that engage young children in general and young girls in particular in science.*
- *Support programs and resources that engage parents and children together in science and provide resources for parents in how to encourage their child's interest in science.*

Space-Weather Education for the General Public

There is a growing awareness within the general public about the nature of the Earth's environment and how people's lives are affected by changes in the environment. Yet overall, there is very little awareness in the general public about how the space environment (i.e. Sun-Earth connection, space-weather) affects peoples' lives.

There are encouraging signs that awareness of space-weather is increasing in the general public. For example, *The Daily Show*, a popular television satirical news show, broadcasted a spoof of the 2003 Halloween coronal mass ejection space-weather event. Unfortunately, media attention of space weather often capitalizes on drama and plays on peoples' fears. In August 2010, one news media outlet reported on a coronal mass ejection with the sensational headline "Solar Tsunami to Strike Earth" (Fox News, 2010).

In order to critically evaluate the risks that such space-weather events pose, it is necessary for the general public to have a greater depth of understanding about the underlying science concepts. However, a preliminary gap analysis of the American Association for the Advancement of Science *Project 2061 Benchmarks for Science Literacy* (AAAS, 2009) conducted by the NASA SMD E/PO Heliophysics Forum indicates that heliophysics-related content does not fit well into Grades K-12 curricula. This means that many Americans may never be exposed to space-weather content in formal education settings. Therefore, out-of-classroom experiences are an appropriate context in which to educate the general public about space environment.

Recommendation:

- *Provide funding for E/PO programs that educate the general public about space-weather and the Sun-Earth connection.*

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SPACE WEATHER FORECASTING THROUGH ASSOCIATION.

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This white paper advocates for a strong community participation to tend to the growing needs of short- or long-term space weather forecasts and for a constant presence of a monitor at L1. Despite advancement in space probes and instruments aboard satellites such as Solar TErrestrial RElations Observatory (STEREO), Advanced Composition Explorer (ACE), and Thermal Emission Imaging System (THEMIS), the ability to provide accurate long- or short-term forecasts still remains an unsolved problem. However, complementing the data are physics-based Magnetohydrodynamic (MHD) models, empirical and semi-empirical models and advanced non-linear computational techniques such as data assimilation, which are still evolving, to help pave the way toward better forecasting.

Researchers using ground and space-based imagers monitor the Sun for active solar structures that are likely to erupt with a solar flare and/or Coronal Mass Ejection (CME). These eruptions can now be observed by and reconstructed in 3-dimensions by imagers aboard the STEREO spacecraft. These initial signatures are crucial for space weather forecasters as they can provide input into MHD models of the solar wind, which allows an approximate prediction of the timing and intensity of the CME as it approaches Earth. For example, major space research thrusts such as the Center for Integrated Space Weather Modeling (CISM) and the Michigan Center for Space Environment Modeling (CSEM) are focussed on developing such comprehensive Sun-to-Earth models. However, these state-of-the-art models do not yet run routinely in *real time*.

In the US, the Space Weather Prediction Center (SWPC) under the auspices of National Oceanic and Atmospheric Administration (NOAA) is the sole and official source for space weather alerts and warnings. We have entered a new era in space weather forecasting requiring more time and effort to handle critical data thanks to probes such as the Solar Dynamics Observatory (SDO) for "hi-def" images of the Sun's corona. Given the copious data available to the SWPC for space weather forecasting, they can be tackled better through local and international alliances; for instance, occasionally, the SWPC's nowcast models are prone to processing delays. Forecasters themselves should come from various academic or private sectors besides the government. Providing free or sparingly low-cost user subscription service helps promulgate and create public awareness of the perils of space weather when it comes to safeguarding space- or ground-based technologies and to prevent communication failures.

Another issue that the heliophysics community must focus on is finding plausible approaches that offer valuable insights to the direction of the solar wind IMF. Though we still lack knowledge of the exact geometry and propagation of the CME, the Wang-Sheeley-Arge model offers initial clues on the polarity of the IMF; giving the polarity to a great degree of accuracy is tough today. Unfortunately, at present, the ACE spacecraft is the "only" farthest upstream monitor, lying 1.5 million km from the Earth on the Sun-Earth line, that reliably provides the critical data on the in-situ solar wind and IMF conditions. Thus, with the ACE having overserved its lifetime expectations, there is a critical need for an accurate upstream solar wind monitor that can measure the speed of the solar wind and its magnetic field direction. Here again, participation from all fronts of the community from initial design to streaming the data live to various end-users is important.

Career Development for Postdoctoral and Early Career Scientists

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I. Demographics: Who are Early Career Scientists?

According to the American Institute of Physics [1], only about 15% of newly-minted Ph.D.'s in physics and astronomy can expect to receive a tenure-track academic appointment for their first job. Instead, almost 60% will take a postdoctoral or other temporary position, with the majority of the remainder taking positions outside physics. Postdoctoral positions are typically 2-4 year fixed term positions, intended to provide a young scientist with additional training before moving into a permanent position. Other temporary positions (with various titles such as research scientist or lecturer) are usually funded out of spacecraft mission or grant proposal funds ("soft money"). These positions often disappear when this funding runs out. Many young scientists will take a series of postdoctoral or other temporary positions before landing a permanent position. Though numbers specific to space physics are not available, in 2007 the NSF estimated that, over all the physical sciences, there were 6,700 postdocs and 1700 research staff with doctorates in academic institutions across the U.S. [2]. These estimates do not include physicists at national laboratories or industry positions.

The numbers of early career solar and space physicists are likely to increase substantially as a consequence of the previous decadal survey, so this survey must address their needs. The previous decadal survey noted "a shortfall at the base of the pipeline for future researchers, instrument developers, faculty and mentors in solar and space physics"[3], and it recommended the addition of 20 faculty positions in these areas between 2004 and 2009. This faculty development program has succeeded in bringing many new undergraduate and graduate students into space science, and these students are now beginning to graduate to the ranks of early career scientists with uncertain futures. This decadal survey must address the concerns of these early career solar and space physicists: the availability and security of funding, work-life balance and career diversity.

II. Timeliness in Space Physics: Early Career Issues with Proposals and Funding

The time it takes to get new scientific ideas into the community is of particular concern to early career scientists, who must quickly demonstrate independent research and funding success in order to secure a permanent position. The average length of a postdoctoral fellowship is 3.8 years [4]. Although little hard data is available on the lengths of early career soft money positions, several years is typical. However, as is shown in Figure 1, the typical time line of a scientific project is of longer duration than these temporary positions, creating significant hardships for early career scientists in demonstrating the value of their ideas.

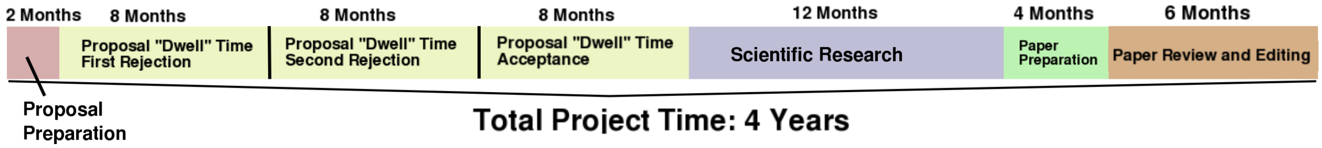

Figure 1: Typical time line of a scientific research project, from idea to publication, developed using publicly available data [5,6,7].

Writing grants is a high priority for early career scientists, but the length of the grant application process and the duration of awards make it unprofitable for hosting institutions to encourage postdocs to write proposals. According to a survey done by Sigma Xi [8], 2/3 of postdocs want to improve their grant writing skills, and this improvement requires practice. However, the typical time between proposal submission and funding start date is around six months to a year (12-25% of the total length of an appointment). Most researchers must submit multiple proposals before receiving an award, drawing out the process even more [9,10,11]. When a grant is awarded to a postdoc, the institution that supported the proposal writing may only receive a small portion due to its multi-year duration. Consequently, many institutions do not allow postdocs to apply for funding as Principal Investigators, making it difficult for a young scientist to establish a track record of independently funded research.

Proposal writing is becoming a higher stakes game to the detriment of the entire community, but this trend is especially worrisome for early career scientists struggling to land their first grant. According to published NSF statistics [12], the chances of NSF proposals in the various areas of solar and space physics being funded dropped by a factor of 2 between 2002 and 2008 (see Figure 2). At present, about a third of

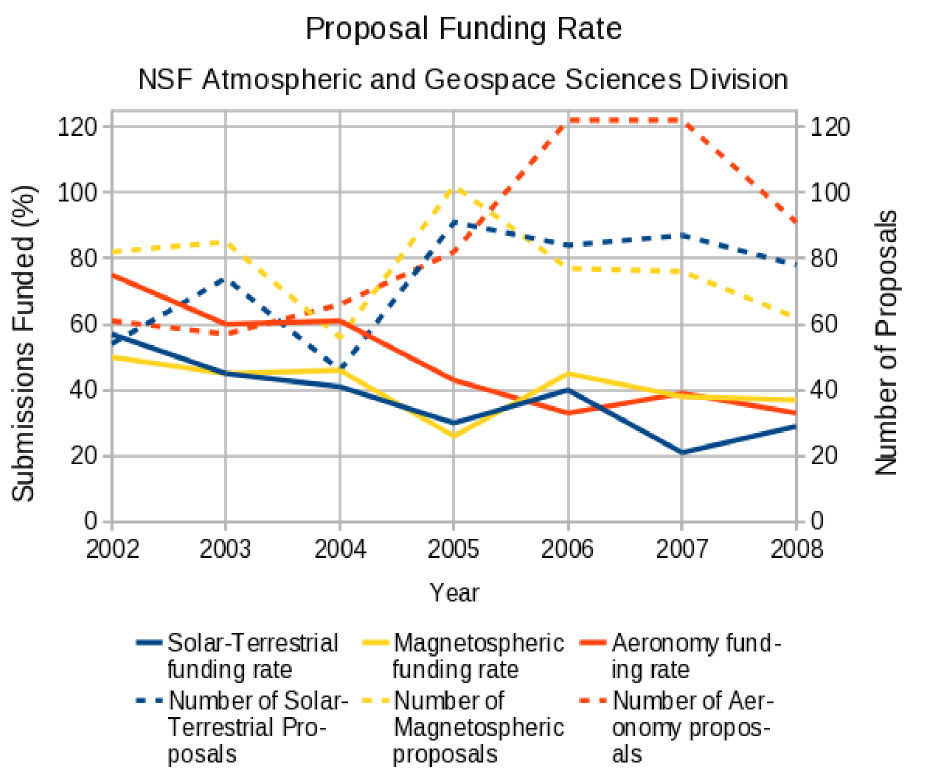

Figure 2: As the number of proposals submitted to the NSF between 2002 and 2008 increased, the percentage receiving funding dropped. Though data for 2009 is available, we have omitted it due to distortions from stimulus funding. These data are raw data, and do not take into account some changing accounting of which federal agency owns which proposal, but the general trend is illustrative [12].

proposals are funded. The drop was probably driven by an increase in submissions produced by circumstances outside the scope of this review (e.g. flat or decreasing budgets in academia, loss of tenure track academic positions and loss of mission funding). Early career PIs are about 20% less likely to be funded than late career PIs [13]. When extrapolated to the numbers from the graph, the success rate of early career PIs in securing funding is probably only about one in four. While receiving money from programs solely available to young scientists is useful, postdoctoral or early career fellowships do not demonstrate that the early career scientist will be successful when competing with more senior scientists. These trends suggest that early career scientists have to submit many more proposals than did early career scientists in previous years to prove they can be successful in securing competitive funding.

Recommendations:

- Create a parallel, low-stakes pool of grant money open to all scientists.

Young scientists need to demonstrate funding success in competition with more senior scientists, and money dedicated to a few postdoc fellowships does not allow this sort of demonstration. A program with a shorter review schedule, shorter than typical award length and a low cap on award amount would give early career scientists timely feedback on grant proposals and quickly allow them to demonstrate success at independent research. A low-stakes pool would benefit all scientists, as it would allow them to explore new projects without having to draw on funds dedicated to other projects. This pool could be created by simply funding four projects at a level 1/4 the size of a typical award.

- Consider the use of pre-proposals to provide quick feedback and early decisions.

Many fields use pre-proposals to narrow down the number of full proposals a panel has to review, while giving quick feedback on major defects to proposals that will not be funded. These pre-proposals are significantly shorter and less detailed than a full proposal and are significantly less time-intensive for both writers and reviewers. A quick rejection is beneficial to early career scientists and all applicants, as they can take the feedback provided to improve the proposal and submit it to another opportunity without the long dwell time.

III. Availability and Security of Funds for Early Career Scientists

The gradual loss of small missions in favor of a few large missions creates career insecurity for young scientists. According to NASA's mid-term analysis of the last decadal survey, "Nearly all of the moderate NASA space missions recommended in the decadal survey have seen multi-year delays... or have been indefinitely deferred." That report also states that, at the time of the previous decadal survey, NASA's Explorer Program was producing one or more missions per year, but by 2009 that rate had dropped to one every four years [14]. Suborbital balloons and sounding rockets, as well as NASA's Explorer Program are necessary for young scientists to develop the skills to lead missions in the future.

The erosion of post-launch analysis money is doubly difficult for young scientists, as it creates both funding insecurity and training gaps. Postdocs and soft money scientists depend on existing missions for training in performing data analysis and building flight hardware. Data analysis money from large missions provides some job security over the duration of a postdoctoral position. In recent years, early career scientists are ever more dependent on an ever-shrinking pool of missions for funding and training, The one year suspension of NASA's Heliophysics Guest Investigator program, as well as the need to make up data analysis funding shortfalls for SDO out of the Living With a Star Targeted Research & Technology program, are worrisome signs of future problems in this area.

Recommendations:

- Protect science funding for small missions and post-launch data analysis.

Funding agencies must support a robust program of suborbital projects and small, frequent space flight missions to allow early-career scientists opportunities to develop mission-critical skills. Post-launch science money for larger missions provides funding security for postdocs and early-career scientists over the entire term of their position, so drawing on this money to cover pre-launch overruns is devastating to the community.

IV. Work-life Balance for Postdocs and Early Career Scientists

The increasing time young scientists are expected to spend in temporary positions following a Ph.D. is enough of a strain to cause some young scientists to leave the field altogether. Young scientists finish their Ph.D.'s typically during their mid to late 20s, and 3/4 of postdocs are under the age of 35 [15]. The late 20s and early 30s are prime years for starting families, particularly for women, whose fertility decreases substantially in their late 30s. Young scientists who want families will frequently have infants or small children during their postdoc years. However, many postdoctoral positions do not offer paid family, vacation or medical leave, and most postdocs cannot afford unpaid leave. The Family and Medical Leave Act only requires employers to give unpaid leave if an employee has worked for that employer for at least 12 months. As a result, young scientists in a series of 2-4 year positions are only eligible for unpaid leave a fraction of the time. A 2010 survey by the Association of Women in Science found “68 percent reported that work-life balance issues had a definite impact on their decision to have or delay having children; meanwhile, 70 percent reported either not taking advantage of or not having access to work-life balance resources.” [16] If the solar and space physics community wants to continue to attract young talent, these work-life balance issues must be addressed.

Starting a family has a variety of negative consequences for the careers of young scientists beyond simple loss of income. Most universities and research institutions use metrics for career advancement to more permanent positions. These metrics include criteria such as number of classes taught or number of first author papers. If an early career scientist needs to take time off for maternity or family leave, their score in these metrics can be significantly lowered. Additionally, taking significant leave or working part-time in order to care for young children can stretch out a project beyond the typical 3-4 year grant duration and increase the time before certain career milestones are reached.

Recommendations:

- Provide paid parental leave for solar physics / space physics / heliophysics postdoctoral fellowship recipients, and offer grants covering salary and benefits for short-term parental leave for other space scientists.

Many postdocs in other fields now have access to paid family leave. For example, the National Institute of Health Ruth L. Kirschstein National Research Service awards offer 30 days of paid parental leave [17]. Extended leave should be available for special circumstances, such as medical complications surrounding pregnancy, since many postdocs are not considered employees and thus are not eligible for state or institutional disability benefits. Family-friendly policies like this one go a long way towards preventing talented young scientists with families from leaving science. While general policies for funding agencies are out of the scope of this review, changing policies for postdoctoral fellowships and offering parental leave grants would be steps in the right direction.

- Encourage funding review panels and other decision-makers to take parental responsibilities into account when setting time lines.

Many postdoctoral fellowships or other career development funds include as a criterion for eligibility a maximum number of years post-Ph.D, or they have a specified funding duration. Though some programs have criteria and durations that take time off for family responsibilities into account, not all do, and all should. No-cost extensions of grants, including postdoctoral fellowships, for parental leave should be mandatory and automatic, as having to negotiate for this leave puts young parents at a disadvantage compared to childless scientists.

V. Diversity of Solar and Space Physics Careers

The field of solar and space physics is at a unique crossroads between academic and applied science, and a typical career will include research projects in both areas. Solar activity presents hazards to polar aviation, suborbital flights, users of global positioning systems (GPS), the electrical industry and space-based defense projects. Industry and government thus have an economic interest in supporting basic research, and career opportunities in these areas have been expanding while those in academia have been flat or falling.

The Executive Branch has directed NASA to work with private industry to build the next generation of space transportation[18], but the young scientists who will make up a crucial part of this effort receive little exposure to how private and military space organizations do research. Graduate education often lacks training for the applied work that is done in national laboratories, federally funded research and development centers, and the industries that fulfill government contracts. Any training that is given is at the discretion of the specific university and department. During interviews conducted for this white paper, industry and defense scientists inevitably described the negative reactions they received from academic scientists during their transition to their first non-academic position: many academic scientists (though certainly not all) view industry positions as "lesser" and the scientists who take them as "failures." This attitude is counterproductive to establishing a diverse and thriving heliospheric community.

Recommendations:

- Continue and increase efforts to reach out to industry recruiters and industry scientists with invitations to attend conferences.

Conferences represent golden opportunities for young scientists to network and establish new collaborations. Face-to-face communication goes a lot farther towards landing a position than e-mail or phone contact. Industry and defense organizations are always looking for candidates with strong technical skills and expertise in space issues, so they would welcome the chance to meet with graduate students and postdocs with research experience in solar physics, space physics and heliophysics. Informal discussion between young heliophysicists and postdocs and industry/defense scientists will help young scientists pursue training in areas important to the aerospace industry, particularly technical writing, computer programming and engineering.

- Create a centrally-maintained list of past Ph.D. recipients who have gone into industry and defense positions who are willing to talk with young scientists.

Even if invited, only a small number of industry and defense scientists will be able to attend conferences. A centrally-maintained list, accessible to all young scientists, will allow students to find someone in their geographic area or research area who can answer questions about particular places to work. This initial contact may be a catalyst for future interactions and collaborations between academic and applied science.

- Create a graduate student and postdoc space physics internship program.

A flexible, fairly informal and extremely low-cost graduate/postdoc internship program could go a long way to improving career opportunities for young scientists as well as fostering collaboration between academic and applied science. Internships like these would give young scientists funding to work at an applied research job in the defense or aerospace industry part time, perhaps a day or two a week or for a single summer or semester, outside their normal postdoc or graduate student duties. Just as undergraduate internships often lead to post-graduation careers, graduate and postdoc internships would broaden the experience of young scientists, leading some of them from academia to industry. It would also ease some of the budget crunch on graduate and postdoc advisers, as this internship would pay some portion of the graduate student's or postdoc's salary.

VI. Summary of Recommendations

- Create a parallel, low-stakes pool of grant money open to all scientists.

- Protect science funding for small missions and post-launch data analysis.

- Consider the use of "pre-proposals" to provide quick feedback and early decisions.

- Provide paid parental leave for solar physics / space physics / heliophysics postdoctoral fellowship recipients, and offer grants covering salary and benefits for short-term parental leave for other space scientists.

- Encourage funding review panels and other decision-makers to take parental responsibilities into account when setting time lines.

- Continue and increase efforts to reach out to industry recruiters and industry scientists with invitations to attend conferences.

- Create a centrally-maintained list of past Ph.D. recipients who have gone into industry and defense positions who are willing to talk with young scientists.

- Create a graduate student and postdoc space physics internship program.

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The International Space Station as a Space Physics Observation Platform V2

Andrew Christensen (Aerospace), Scott Budzien (NRL), Andrew Stephan(NRL), Rebecca Bishop (Aerospace)

For the past year, a remote sensing limb-scanning spectrometric mission has been operating on the ISS. This instrument suite of eight separate spectrometers and photometers comprises the RAIDS experiment, developed jointly by the Naval Research Laboratory and The Aerospace Corporation. The experiment was launched in September 2009 as part of the HICO-RAIDS (HREP) Experiment Payload on the inaugural voyage of the H-IIB rocket and the H-II Transfer Vehicle (HTV), a Japanese unmanned resupply capsule for the ISS. HREP became the first US payload to be attached to the Japanese Experiment Module (JEM) Exposed Facility on the Kibo module. HREP/RAIDS is serving as a pathfinder mission for performing atmospheric remote sensing aboard the ISS, This paper summarizes the experiences of the RAIDS team relevant to the use of the ISS as a science platform.

NASA has placed a priority upon maximizing the scientific return from ISS user experiments, and the space agency has been very cooperative with the RAIDS team throughout the planning and operational phases of the project. During the startup phase of the RAIDS mission there was some confusion about mission operations, policies, information system access, and communications with NASA. Some of these difficulties originated in the extremely short development times for HREP/RAIDS and in RAIDS being the first external limb-viewing payload, which presented new operational challenges. However, after overcoming the roughness of the startup phase, we have established clear lines of communication with NASA. They have been very responsive to our needs, including, for example, by providing unscheduled real time commanding and data feeds and by responding quickly to our concerns on attitude stability.

A partial history of the ISS altitude is plotted in Figure 1. During the past year the altitude has averaged near 350 km. An example for Sept 13, 2010 is shown in Figure 2. The inclination of ISS is 51.6 degrees with a period of 91 minutes.

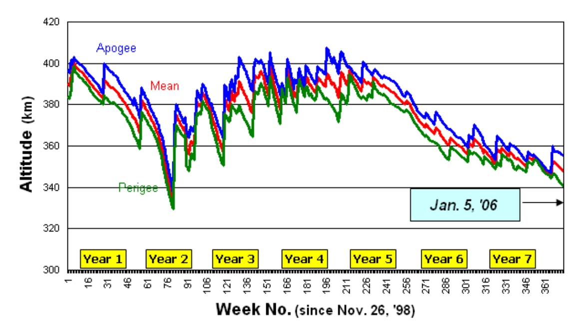

FIGURE 1. ISS altitude history: *Apogee height* -- *Mean Altitude* -- *Perigee height*

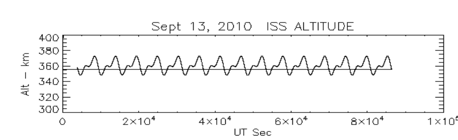

Figure 2. ISS altitude profile for one day, September 13, 2010.

The Japanese Experiment Module, or JEM, called Kibo -- which means "hope" in Japanese -- is Japan's first human space facility and enhances the unique research capabilities of the International Space Station. Kibo consists of six components: two research facilities -- the Pressurized Module and Exposed Facility; a Logistics Module attached to each of them; a Remote Manipulator System; and an Inter-Orbit Communication System unit. Kibo also has a scientific airlock through which experiments are transferred and exposed to the external environment of space. The instruments are attached to a port on the Exposed Facility (porch) as shown in Figure 3. The instrument is held by a manipulator arm and plugged into the port which supplies mechanical support as well as power and communications with the experiment.

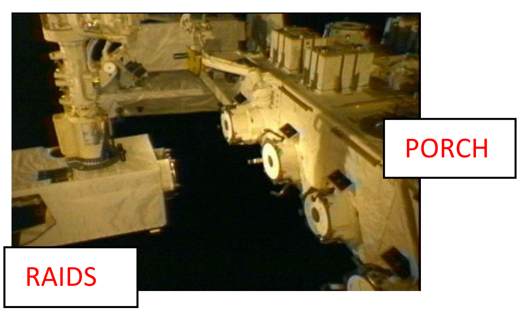

FIGURE 3. The HREP instrument package which includes both the HICO and RAIDS experiments is pictured during the attachment to the KIBO porch on the ISS.

The KIBO module and its porch to which the RAIDS is attached is indicated in Figure 4. The ram direction is out of the page. It is evident that in the anti-ram viewing configuration, there are ISS structures in the foreground of the sensor fields of view that are sources of scattered light from the sun and Earth. Viewing in the ram would avoid these sources. RAIDS is mounted to view the Earth’s limb in the anti-ram direction chosen to minimize the collection of out-gassed materials on the optical surfaces, but this configuration has impacted the analysis of some sensor data due to these scattered light issues.

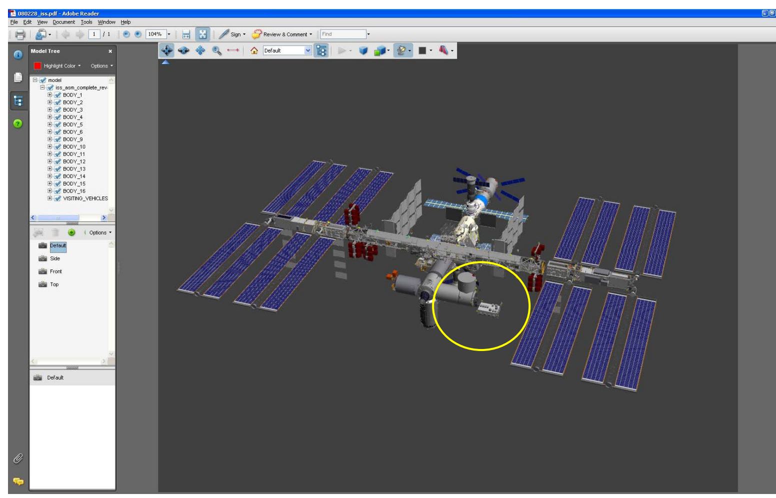

FIGURE 4. Sketch of the ISS with the location of Kibo and its attached Exposed Facility to which the HREP package was attached is indicated. The ram direction is out of the page.

Some of the items that are of interest to scientists planning to use the ISS as an observatory are summarized below.

Pointing Issues

The ISS in normal operations (no Soyuz or Shuttle docked) flies with the X coordinate of the station in the ram direction (Figure 5). However, during Shuttle and Soyuz docking and at other times the ISS attitude undergoes large changes. It may be pitched toward the Earth up to 90 degrees or yawed up to 180 degrees. Initially, it was our experience that these attitudinal changes sometimes occur without prior knowledge of the science team. However, after a lengthy process of gaining access to NASA information systems, the RAIDS team eventually obtained Attitude Time Line updates, which provide about 1 week notification about attitude changes.

During normal operations there are oscillations in pitch, roll, and yaw with periods of approximately 45 minutes (1/2 orbit) arising from torques on the large, rotating solar arrays. The amplitude depends on the attitude controller units utilized by the ISS. Using the ULF-4, the amplitude of the pitch and roll oscillation is approximately ±1 degree as shown in Figure 6.

With the new ULF-5 mixed/blended controller the pitch is maintained to ± 0.35 degree as shown in Figure 7. The corresponding roll amplitude is approximately 0.4 degree. The ULF-5 controller was implemented on the ISS in October in preparation for the final ISS module configuration. In mid-summer 2010 in response to the need for greater stability of the pitch oscillation expressed by the RAIDS team, NASA specially implemented the older 2JA momentum controller to provide ± 0.2 degree pitch stability.

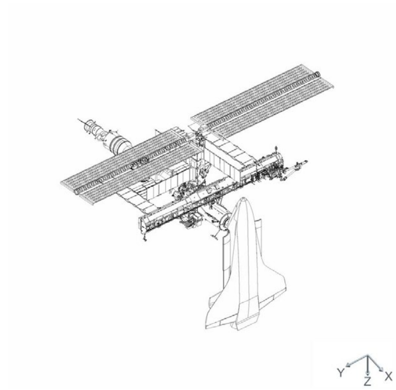

FIGURE 5. Sketch of the ISS indicating the body coordinates of the system.

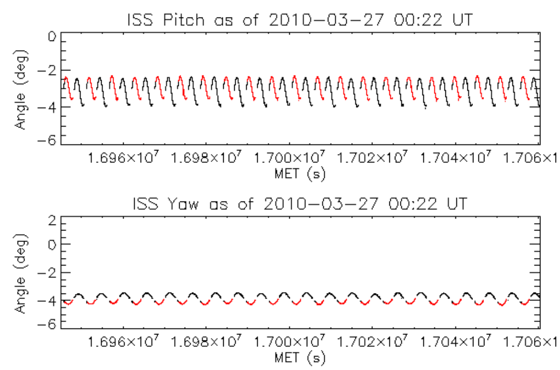

FIGURE 6. Pitch and Yaw with the ULF-4 controller on the ISS

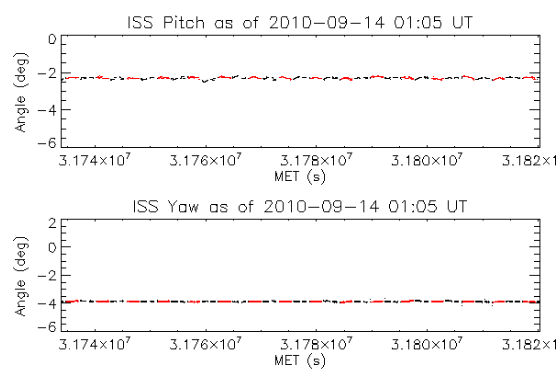

FIGURE 7. Pitch and Roll of the ISS using the ULF-5 attitude controller on the ISS.

The RAIDS instruments except for the FUV spectrograph are attached to a scan platform that nominally sweeps the instrument FOVs vertically on the limb from approximately 90 to 300 km. Knowledge of the zenith angle with respect to the local vertical is very important for limb scanning type observations. For RAIDS, the requirement was zenith angle knowledge <0.05° The team was not sure how closely the attitude data reported by the ISS would apply to our instrument located on Kibo. Therefore, to meet our pointing requirement, a star tracking instrument was attached to the HREP enclosure. We have been able to interleave the attitude data from these two sources to meet the RAIDS pointing requirement. Comparisons of the attitude reported by our star tracker and the ISS show relative agreement to the 0.001 degree level. At the present time the absolute biases between the ISS and star tracker attitudes have not been determined, since our practice has been to scale and interpolate the ISS values to fill-in missing star tracker attitudes. Without a star tracker our pointing knowledge would be dependent on the mechanical mating tolerances of the experiment to the ISS and possibly the location of our payload on the ISS. The requirements for yaw and roll knowledge were substantially relaxed (about 5x) compared to pitch.

Scattered Light

The RAIDS photometers and spectrometers view aft from the Kibo porch. From this location, there is ISS structure in the foreground of the instruments. Although, they have extended baffles, there is some scattered light that is detected by the PMT's in the near-IR region sensors. The EUV , FUV, mid-UV and near-UV instruments are not sensitive to the scattered light. The scattered light varies by orders of magnitude depending on the location of the sun with respect to the ISS. Figure 8 is an example of photometer limb scans separated by several minutes. The data above approximately 120 km tangent altitude are subject to scattered light from the ISS.

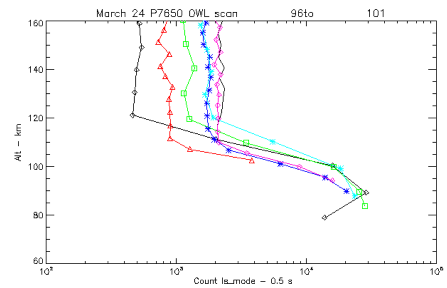

FIGURE 8. The observed PMT counts from successive limb scans of the dayside airglow layer at a wavelength of 765 nm. The count rates at the upper altitudes are strongly affected by scattered light from ISS structures in the foregrounds of RAIDS.

Contamination of the Optics

Initially there was great concern on the experiment team regarding contamination of optical surfaces in the instrument and a subsequent loss of signal, especially in the EUV instrument. The instruments have been operating in the ISS environment for the past year. There is no indication of significant impact to sensor capability due to loss of signal on the mid-UV, near_UV, nor near_IR instruments. The EUV instrument has exhibited a slow loss of count rate during the year, but the original count rate has been reestablished by increasing the gain of the EUV micro-channel plate detector. It is not yet clear to what extent the loss of gain is attributable to contamination of the optics or the open detector. Neverthless, the instrument has retained its full science capability now over one year into the mission.

The plot in Figure 9 shows the combined effect of detector gain sag and contamination on the total responsivity of the RAIDS EUV sensor. The data show total counts measured across the entire 800-1100 A passband compared to data from initial sensor operation in late October 2009. These measurements were collected at nearly identical solar zenith angles and conditions, with only minor differences in the solar F10.7 index. These data were all obtained prior to the first high voltage adjustment that allowed some of the loss to be recovered. The red symbol indicates the median values of these ratios, fit with the blue line showing a 0.2% drop per day from the initial sensor responsivity.

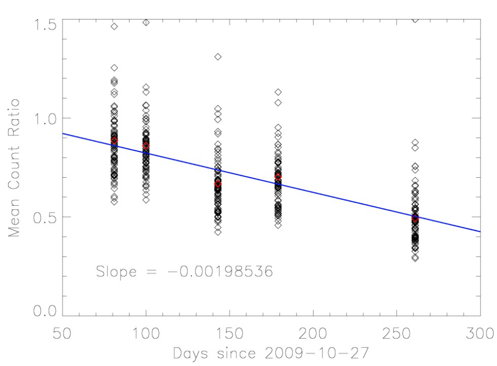

FIGURE 9. Count degradation of the EUVS in the RAIDS experiment on ISS during the first 9 months on orbit.

Preflight testing and certification

The RAIDS experiment was originally designed to be launched on a TIROS satellite and had therefore been designed mechanically and electrically for that platform and launch environment. To meet the requirements for the launch and operation at ISS, several changes and studies needed to be completed for RAIDS as summarized here.

- Safety Review
  - Three stages of Safety Review
- Design Analysis
  - Analysis of existing basic mechanical design
  - Re-scoping of the test environment
  - Replacement of fasteners on the experiment
  - New electrical interface
  - Changes to the thermal system
  - Additional of survival heater busses

The RAIDS team held a kickoff meeting in March 2007 and shipped the instrument two years later to Japan in April 2009. During that period the mechanical, electrical and thermal designs were examined in light of the new launch vehicle, processing and attachment to the ISS and operations in the ISS environment. This led to new testing requirements to verify compliance with new launch loads and new electrical and thermal interfaces.

As a result of the analyses, all the screws in the payload were replaced. A Power Distribution Unit was added to the instrument to interface between the original TIROS electrical interface and the ISS interface. The location and thickness of thermal blankets were also adjusted to fit the new thermal environment.

A significant difference between a normal space experiment and the ISS experiment is the range of thermal environments experienced by the instrument. In our case we had five survival heater busses for the following configurations.

- Launch phase
- Docked at the ISS but still in the launch capsule
- Robotic transfer phase
- Storage on the JEM
- Operations

The requirements for placing an experiment aboard the ISS means satisfying requirements in several areas. Developing ISS payloads does require analysis or testing to demonstrate compatibility with several different interfaces, namely, the payload carrier on the launch vehicle, the on-orbit installation interfaces, the ISS itself, and any disposal interfaces required. The number of interfaces involved is higher than a typical satellite mission, where one is only concerned about the experiment-spacecraft interface.

Any spaceflight mission entails optimizing risk within the trade-space of hardware resources (mass, power, telemetry), budget, and schedule. Manned-mission safety compliance is commonly perceived to be a budget-buster. However, the HREP development team found that the generous resources available to payloads on the ISS led to engineering design and hardware cost savings, which help offset the effort required for safety compliance. Moreover, the simplified engineering approach adopted by the development team was critical in enabling HREP meet an unusually compressed development and testing schedule of two years from design to delivery.

Since there are a variety of manned and unmanned vehicles to carry payloads to the ISS, the requirements for launch can vary widely. Since RAIDS was carried by an unmanned vehicle, there were no onerous safety concern as might be the case for a Space Shuttle payload. The analysis and environmental testing required to demonstrate compatibility with ISS interfaces was no different than that of any space mission. An added dimension is the manned mission safety process, which includes a sequence of formal reviews in a parallel track with the typical mission design review process. This consisted of Phase 0/I, Phase II, and Phase III Safety Panel reviews which addressed a wide variety of mechanical, electrical, chemical concerns. A number of analyses of high voltage devices, the launch lock mechanism, and astronaut EVA safety were performed.

Operations – Commanding and Data Telemetry

Upon connection to the Kibo porch, power and communication with the experiment was established within a couple of days. The data were downlinked from TDRSS to White Sands, routed to NASA Marshall SFC, and directly streamed over the Internet to the Naval Research Laboratory for analysis and archiving. This system worked very well. There were no anomalies in the commanding and data link operations. The early orbit checkout of the RAIDS experiment was facilitated with scheduled daily command windows including weekends. In addition, NASA was usually able to support unscheduled command windows depending on ISS operations. . Since initial sensor checkout, RAIDS and HREP have been conducting routine commanding sessions through the scheduled 4-hour window available every weekday as well as occasional special command windows that have been granted through requests to NASA and the ISS Payload Operations Director. The receipt of ISS ephemeris and attitude data was worked out within the first couple of months of operation and has been consistently available since then.

Summary

A remote sensing space experiment, the RAIDS payload, has been successfully operated on the International Space Station since Oct 2009. Our experience has demonstrated that the Exposed Facility on the JEM module is suitable for siting optical instrumentation and conducting scientific experiments. The attitude of the ISS can be adequately controlled so in combination with an experiment dedicated star tracker very accurate knowledge of the pointing direction can be known. The contamination environment appears to be a non-factor in the performance of the instrumentation and NASA has worked out the procedures for commanding and data communication that works very smoothly. We conclude that the ISS provides a space observing platform that has many advantages and should be seriously considered as a new opportunity for solar and space physics research.

The High-Latitude Solar-C International Collaboration: Observing the Polar Regions of the Sun and Heliosphere

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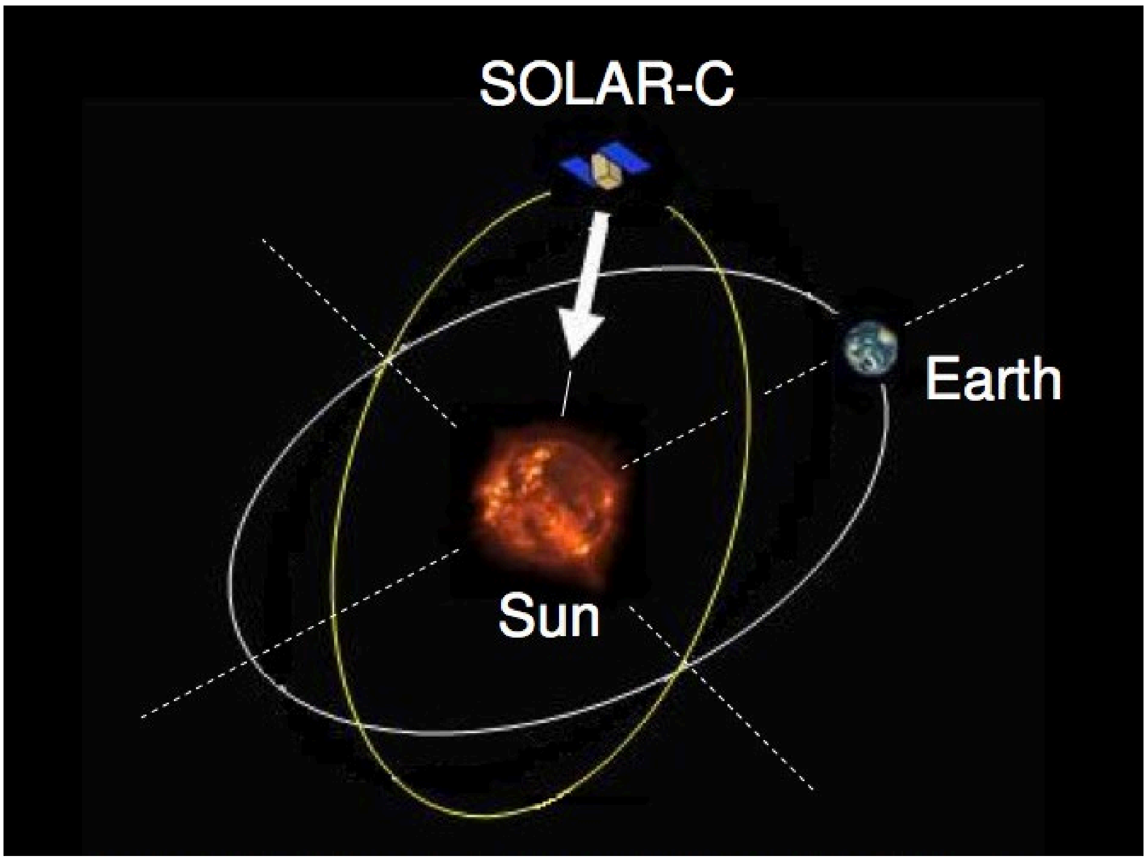


Abstract
The Solar-C mission will follow the scientific success of the previous two international collaborations between NASA, the Japanese Aerospace and Exploration Agency (JAXA), and Europe. The "Plan A" mission proposes to fly a focused suite of instruments designed to study the solar interior flows (by helioseismology), surface magnetic fields, transition region, and extended corona from an orbit inclined at least 40 degrees to the ecliptic plane. The instrument complement in the baseline mission design and the orbital inclination angle to the ecliptic have been selected to address specific outstanding issues in solar dynamo theory and the acceleration of the solar wind. Optional instruments under consideration will image CMEs directed at the earth and collect in-situ measurements of the mid-latitude solar wind. The data collected in combination by Solar-C Plan A, Solar Probe Plus and Solar Orbiter, as well as data from near-earth observatories like SDO or GOES-R SUVI, will provide composite data sets that will

significantly advance key aspects of the solar dynamo, solar wind acceleration, CME formation and propagation, and energy transfer from the photosphere to corona. Participation in such a large-scale, international collaboration led by Japan will leverage a relatively small investment from NASA to produce an extraordinary scientific return.

Introduction

Understanding the origins of solar magnetic activity has been at the forefront of solar physics since the discovery of the 11-year sunspot cycle nearly two centuries ago. Unraveling this mystery has broad implications not only for promoting a deeper knowledge of the Sun itself but also for understanding the Sun's influences on the heliosphere, the geospace environment, and the Earth's climate system. Such influences regulate space weather, with increasing economic impacts on our technological society as our reliance on telecommunications systems, power grids, and airline travel continues to grow. As a readily observable example of an astrophysical magneto-hydrodynamic (MHD) dynamo, the Sun also provides unique insights into the generation of magnetic fields by turbulent plasma flows throughout the universe, from planetary and stellar interiors to stellar and galactic accretion disks to interstellar clouds.

The global magnetic polarity of the Sun reverses during each 11-year sunspot cycle. Understanding how such regularity arises from the highly turbulent conditions of the solar convection zone, and how magnetic flux emerges from the solar interior to power solar variability is a formidable challenge. The polar fields reverse at about the time of sunspot cycle maximum. While it is clear that this reversal results from the transport of magnetic flux elements in the near surface layers, it is unclear which processes dominate this transport. The axisymmetric meridional flow (which dominates at low latitudes) may not extend all the way to the poles. While the horizontal random-walk of vertical magnetic structures by the evolving cellular convection should extend to the polar regions, the role of the radial transport of the ubiquitous horizontal fields remains very uncertain. The polar fields reach their maximum strength near the end (minimum) of each sunspot cycle. This field strength has been shown to be the best predictor of the size of the following sunspot cycle but how the polar fields are translated into sunspot fields is still highly uncertain. Thus, for developing physics-based forecasts of solar activity, it is extremely important to investigate the structure and evolution of the polar magnetic fields and the mechanisms of magnetic flux transport.

Modern solar observations coupled with sophisticated theoretical and numerical models have yielded profound insights into many aspects of solar magnetism but the basic physical mechanisms responsible for generating these fields are still not understood. The Solar-C mission will focus on observations of the magnetic structure, dynamics and solar-cycle evolution of the polar regions of the Sun, providing data of critical importance for our understanding of the solar dynamo mechanism and the cyclic nature of solar activity. This task will be accomplished using instruments that can characterize internal processes occurring inside the solar convection zone and draw the connection to their manifestation on the solar surface and in the heliosphere. By pursuing a complementary and integrated approach between measurements addressing dynamo signatures in the solar convection zone and magnetism at the solar surface, the Solar-C Plan A mission will make great scientific progress in our understanding the Sun and the fundamental problems of cosmic magnetism.

For the past year and a half, solar physicists in Japan, the United States, and Europe, many of whom were involved in the highly successful Solar-A (Yohkoh) and Solar-B (Hinode) missions, have been studying mission concepts that would make major steps forward in solar and heliospheric physics. Participation in such a large-scale, international collaboration led by Japan would leverage a relatively small investment from NASA to produce an extraordinary scientific return. The Japanese solar physics community is currently considering two mission concepts for Solar-C: an out of the ecliptic mission (plan A) and a high-resolution mission (plan B). This white paper gives a brief overview of the science objectives for the plan A Solar-C mission and the instruments and mission design required to achieve them. Further elaboration of the scientific case for polar observations of helioseismology and magnetic fields may be found in a the white paper titled *"The Importance of Polar Observations in Understanding the Solar Dynamo"*.

Science Objectives

The outstanding issues confronting our current understanding of the solar dynamo may be summarized through several key scientific questions:

Q1) What physical processes dominate the generation of global-scale poloidal magnetic fields and where do they operate?

Q2) How does the transformation between the poloidal (polar) and toroidal (active regions) magnetic fluxes occur? How does this regulate the cyclic magnetic activity?

Q3) What are the structure and the evolution of the solar differential rotation, and the mean, large-scale meridional flow, how are they maintained and how do they vary with the solar cycle?

Q4) What is the dynamical origin of photospheric active regions? What is the role of the tachocline?

Q5) How can we predict sunspot cycles and periods of high solar activity?

Progress on these scientific questions requires detailed observations of the solar polar regions, where data is currently scarce and where much of the subtle interplay between plasma flows and magnetic fields that gives rise to cyclic polarity reversals is thought to occur. High-latitude photospheric observations will provide an unprecedented vantage point for helioseismic imaging that can be used to probe flows and fields in the deep convection zone and in the tachocline where solar activity is ultimately thought to originate. With this in mind, we propose the following prime measurement targets for the Solar-C mission:

T1) Differential rotation and meridional flow in the polar regions and the deep convection zone

T2) Photospheric magnetic flux distribution and evolution in the polar regions

T3) Dynamical coupling between magnetic fields and flows

T4) Structure and evolution of solar convection

In addition to measurements at the photospheric level, the structures of the outer solar atmosphere in the polar regions and the heliospheric structures merit observation from outside the ecliptic. The poles of sun undergo dramatic change during the 11-year solar cycle, driven by the dynamo action in the solar convection zone. The polar vantage point gives unique opportunities for understanding the origin of the fast solar wind spectroscopically and for stereo viewing of surface vector magnetic fields, coronal structures, and earth-directed CMEs in coordination with observatories near the earth. The unique inclination for the Solar-C observatory will also permit long term measurements of the total solar irrandiance which may help resolve the discrepancy of the cycle variation of the solar irradiance of ~0.1% while solar analogs vary, on average, by 0.3%. In addition to the solar dynamo studies elucidated above, Solar-C Plan A will also address the follow prime mission questions.

Q6) How does the total solar irradiance change as a function of the solar latitude?

Q7) How do the flows of the outer solar atmosphere in polar regions differ from those at low latitudes and how do they change over the solar cycle?

Q8) How do the global coronal structures extending to the inner heliosphere change in the solar cycle?

These questions motivate the following measurements to understand the dynamics of the polar regions reflecting the solar dynamo actions:

T5) Continuous measurement of the total solar irradiance from various solar latitudes

T6) Imaging and imaging spectroscopy of transition region and coronal EUV lines

T7) White-light imaging of heliospheric structures between the Sun and Earth

T8) In situ measurements of the solar wind and cosmic rays

The focus of science within NASA has remained largely unaffected by the change in political leadership, and the recently released NASA Science Plan for the Science Mission Directorate reflects long-held priorities in Heliophysics. The current National Policy Direction on Earth and Space Science as authorized by Congress lists as a finding that "Human and robotic exploration of the solar system will be a significant long-term undertaking of humanity in the 21st century and beyond, and it is in the national interest that the United States should assume a leadership role in a cooperative international exploration initiative." The Solar-C Plan A mission advances this policy and follows the guiding principals of NASA for international partnerships. This mission will leverage NASA resources in a cost-efficient and effective manner to "accomplish shared science objectives" that are encapsulated in the NASA Heliophysics Roadmap released in 2009. In fact, of all the Research Focus Areas (RFAs) listed in the Roadmap, only two (F3 and H2) are not directly addressed by the Solar-C Plan A mission. Cooperation through NASA sponsorship of instrumentation and scientist support of the Solar-C Plan A mission is of major benefit to the Heliophysics science community, NASA technology development, interagency cooperation to develop co-sponsored missions, and international science collaboration.

Measurement Requirements

The following observables are required to address the Solar-C top science objectives: (A) full-Sun photospheric magnetograms for tracking the evolution of magnetic fields on the surface, and (B) full-Sun photospheric line-of-sight Dopplergrams for measuring the subsurface flows by helioseismology.

These measurements must come from an orbit inclined to the solar ecliptic, with maximum orbit inclination >40 degrees. The orbit must allow observations from >30 degrees inclination for periods of >40 days for each polar passage. To maximize the telemetry available, the orbit shall be circular with a 1-year period, to synchronize the orbital motion of the spacecraft with that of the Earth.

The orbit gives a unique vantage point for the other science objectives. The following observables shall be taken to address them: (C) total solar irradiance, (D) full-Sun chromospheric images, (E) full-Sun transition region (TR) images, (F) full-Sun coronal images to monitor the dynamic activity and the evolution of high-latitude structures, and (G) emission-line imaging spectra in chromospheric, TR, and coronal lines for investigating the source region of fast solar wind, (H) visible-light images monitoring interplanetary space between the Sun and Earth, and (I) in-situ measurements including magnetic field, solar wind protons and electrons (TBD). Currently, (H) and (I) are treated as options in the ISAS/JAXA Interim Report.

Photospheric magnetograms and Dopplergrams are made from multiple images. Not all the images can be transferred to the ground due to the expected telemetry rate, so onboard data processing and compression are mandatory to reduce the total data volume transferred, as was done on SOHO/MDI. The field of view for imaging observations needs to cover the full Sun with sufficient spatial sampling for each observable. The science requirements for image size, cadence and duration for the helioseismic observables are discussed in detail in the Interim Report. The table shows estimates of the required data rates. A total average data rate of ~100 kbps is required.

Measurement		Wave-length (Å)	Spatial sampling	Image Size (Pixels)	Number of images transmitted	Cadence	Data rate (kbps)
1	Photospheric line-of-sight magnetic field	visible	1.0 arcsec 2.0 arcsec	2048×2048 1024 ×1024	1	10 min	*10 *5
2	Photospheric vector magnetic field	visible	1.0 arcsec	2048×2048 256×256	16	8 hours 10 min	*7 *5
3	Photospheric line-of-sight Doppler velocity: Global Helioseismology	visible	4.0 arcsec	512×512	1	1 min	*13
4	Photospheric line-of-sight Doppler velocity: Local Helioseismology	visible	1.0 / 2.0 arcsec	1024 ×1024	1	1 min	*51
5	Imaging of Chromosphere	Visible (TBD)	1.0 arcsec	2048×2048	1	1 hour	#3
6	Imaging of TR and Corona	EUV/X-ray	~1.2 arcsec ~2.4 arcsec	2048×2048 1024×1024	2	1 hour 5 min	#3 #20
7	Imaging spectroscopy of Chromosphere, TR, and	EUV	~1.0 arcsec	spatial×spectral	1	10 sec	*19

	Corona			256×256			
8	Monitoring TSI	-	-	-	-	1 min	2
9	Heliospheric imaging [option]	visible	0.03 deg	1024 ×1024	1	1 hour	*1
10	In-situ (TBD)	-	-	-	-	-	~1

*(#)Data compression down to 3 (1.5) bit/pixel is assumed

Instrument Payload

The science payload to satisfy the primary measurement requirements consists of:

- A visible light imager that can measure the full-Sun photospheric magnetic fields and line-of-sight Doppler velocity, similar to MDI on SOHO or a simplified version of HMI on SDO.
- A total irradiance monitor that measures the irradiance of the Sun. Multiple cavity monitors are needed for self calibration.
- A light-weight EUV imager that monitors the transition-region and coronal activity in the polar region.
- An EUV scanning spectrograph that measures the flow structures in the polar region.

The following instruments provide measurements T7 and T8 and are listed as optional:

- A heliospheric imager that observes the space between the Sun and Earth
- In-situ instruments (TBD)

Trajectory and Orbit

The major mission requirement of SOLAR-C Plan A is to observe the Sun from high latitude, with target specified as 40°. In order to achieve this target, JAXA has studied a number of possible mission designs using various trajectory manipulation techniques. The items considered are the tilt of the solar equatorial plane to the ecliptic, launcher capacity, planetary gravity assists, and the use of a highly efficient propulsion system. The launcher assumed is the Japanese H2A heavy launch vehicle equipped with a solid motor upper stage. There are two possible options: one is to use solar electric propulsion assisted by an Earth swing-by (SEP option), and the other is to use both Jupiter and Earth swing-bys (Jupiter option). The latter is a purely ballistic trajectory. The final orbit is nearly the same, a circular orbit with 1 AU distance from the Sun and 1 year orbital period, with a different time to reach the maximum inclination (5 years for SEP option, and 7 years for Jupiter option). If there is a strong requirement that the spacecraft has to be in the final orbit before the solar maximum around 2024 (assuming launch in 2019), the SEP option is the only currently available way to satisfy the time constraint.

The orbit profile in the cruise phase is quite different between SEP and Jupiter options. In the first three years, no observations are possible for the SEP option, and there may be a short observing period of about a month at each hemisphere in the following years until the spacecraft enters into the final orbit. On the other hand, observations are possible at any time outside the swing-by operation for Jupiter option, but high telemetry is limited to positions near the Earth until reaching the final orbit.

Spacecraft

The SEP option requires a heavy propulsion system. The assumed μ20 ion engine system is an upgraded version of μ10 that was used in JAXA HAYABUSA sample return mission. The new engine itself has undergone endurance testing in the lab but no flight heritage yet. The μ20 ion engine system consumes 6 kW power, and a lightweight solar array paddle with large area is necessary. The total wet weight of the spacecraft in the SEP option is ~1200 kg with payload mass of 130 kg. The total wet weight of spacecraft in the Jupiter option is ~750 kg with payload mass of 130 kg. Both options require a new kick-motor for the H2A launcher.

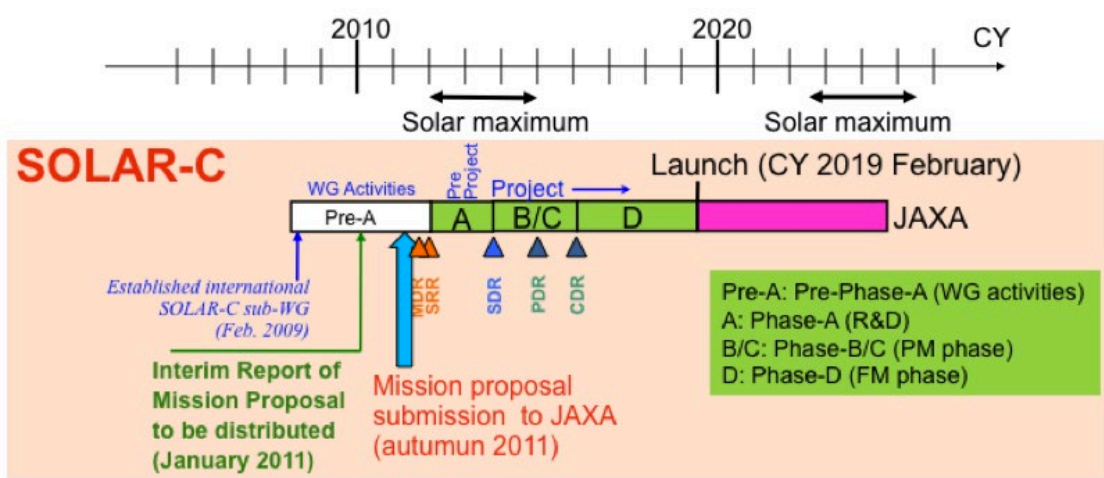
The spacecraft attitude is three-axis stabilized to meet the requirements of the imaging instruments. Angular momentum management occurs daily to weekly, using chemical thrusters.

300 kbps X-band downlink telemetry rate and 8 hr downlink time per day are assumed for an average data rate of 100 kbps, at a spacecraft distance at 0.56 AU from the Earth. Downlink stations are needed in the northern and southern hemispheres on Earth. 1 Mbps Ka-band telemetry rate at the same distance is under consideration to enable a greater telemetry volume.

Mission Cost and Readiness

Solar-C is envisioned as an International Partnership Mission led by JAXA with substantial contributions from NASA and Europe. It is designed to be a Small Strategic Mission from NASA's standpoint; the maximum cost to NASA for such a mission is $250M. This investment will ensure full participation in a large international mission, whose total cost may be of order $750M.

The instruments for Solar-C Plan A do not require any significant technical advances, and examples of most of the instruments have flown already. Some design changes from previous models may be needed to meet the mass and telemetry budgets, but the TRL levels of all are judged to be 6 or higher, with many instruments or major components above TRL 7. Within Phase A comprehensive study on the radiation environment will be completed. As discussed above, the μ20 ion engine has not flown yet, and the tradeoffs between the SEP and Jupiter options are still undergoing intensive study by JAXA. At this time, it appears that both options offer a practical solution for achieving the 40-degree inclination circular orbit with 1-year period. The chart shows the tentative schedule for development and launch of Solar-C.



The Importance of Student Instrument Programs in the Workforce Development in Solar and Space Physics

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Introduction: Why Student Instrument Programs?

Student instrument programs are compelling vehicles to attract, retain and move students through the higher education pipeline into graduate studies and the scientific and engineering workforce. In addition, student instrument programs involve undergraduate students in an authentic research environment that increases their interest in scientific and technical careers and enthusiasm for space exploration, while equipping them with first-class engineering and science skills. These programs are also critical training grounds for graduates students and post-docs aspiring to be the next generation of instrument PIs. Solar and space physics, as a discipline, is particularly amenable to student instrument programs, given the ability to use suborbital platforms to carry out the work, while still producing new scientific results.

Student instruments represent an excellent value and allow us to harness the resources and assets of universities around the country to support the space industry's workforce pipeline. The final report by the NRC Committee on Meeting the Workforce Needs for the National Vision for Space Exploration (NRC, 2007) suggests that while NASA has an adequate pipeline to meet its current workforce requirement, NASA needs to play a role in training the potential workforce in the skills that are unique to the work that the agency conducts. Indeed, this would be a valuable contribution towards training the entire national work force in STEM-related fields. The report suggests that hands-on experiences for students that focus on the unique demands of satellite and spacecraft systems, environments, and operations, and the opportunity to acquire early knowledge of systems engineering and project management techniques is an extremely important investment for NASA to make. In specific, the committee recommended that NASA support university programs that provide hands-on training, and identified suborbital programs as one key to this development. Small satellite programs, such as the CubeSat program (NSF) or the NanoSat program (DoD) can also provide inexpensive and viable opportunities for student engagement.

Higher education, both at the undergraduate and graduate level, is a critical juncture at which to entrain STEM workers. As elucidated in the report "Rising Above the Gathering Storm" (NRC, 2006), failure to capitalize on this moment will have serious consequences for America's standing as a leader in science and technology. Engineering and science programs at the university level have recognized the value of integrated, hands-on educational opportunities. New and exciting work on project-based learning, team problem-solving programs, and the influx of entrepreneurial ideas has been shown to attract and retain students from across the science and engineering spectrum (Froyd and Ohland, 2005; Dym, et al., 2005, Eris and Leifer, 2003). The advent of these programs offers an important 'fertile ground' within which student instrument programs can operate, taking advantage of work that has already begun.

Students involved in student instrument programs often describe their experiences as 'life-altering', with many of them continuing forward towards careers in science and engineering. Students see these programs as meaningful, particularly in terms of knowledge or skills gained. There is the sense that student instrument programs are 'real-world' experiences that will transfer to the future work environment, putting them ahead of their peers with only classroom training.

Lastly, the role of innovation and discovery in student instrument programs cannot be underestimated. Students bring new ideas and thoughts driving their professional mentors to 'think outside the box', providing an environment that nurtures innovation and alternative approaches for achieving success. As a result, student instrument programs allow organizations to develop in-house expertise in technological areas that they haven't worked in previously, building credibility that can be used for later programs. Carefully crafted, these programs can be used to develop heritage for new instruments or technologies.

What are Student Instrument Programs?

The definition of student instrument programs is necessarily broad and flexible to encompass the large range of possibilities these programs entails. These programs often combine science and engineering, whether as part of a suborbital or satellite platforms or as part of instrument design. There is an emphasis on high-quality projects that involve students in multiple segments of the mission from scientific formulation, to mission planning, to systems engineering, to design and development of flight hardware, to qualification, test and integration, mission operations, to ground truthing and data analysis. In general, a well-rounded student instrument project should provide each student with experience in/exposure to a) systems design and development, b) technical skills, c) data collection and analysis techniques, and d) documentation, reporting and reviews. Suborbital platforms, in particular, allow the process to come full circle – from initial science question through the design and deployment to the science answers – in a time frame that fits to a students' education program. The full cycle can be complete in only 1-3 years, unlike a satellite mission that can range from 6-10 years, allowing only certain pieces of the puzzle to be experienced. While most student instrument programs focused at the collegiate level, but broader participation is possible, including the K-12 formal classroom and the broader audience known as 'citizen scientist'.

Student Instrument Programs as Training Ground or More

Undergraduate and graduate students are most often the target for a student instrument programs. For undergraduates, it is because they are at this critical junction of their education when they are making decisions about where and whether to join the STEM workforce. For graduate students and post-docs, student instrument programs provide an important training ground – a place where the next generation of instrument or mission PIs gain a critical understanding of the interplay between science and engineering.

Student instrument programs are primarily collaborative educational experiences, rather than driven by cutting-edge science and technical requirements. That said, student instrument programs offer important opportunities to both conduct authentic scientific research and to create and test new instrument concepts or build instrument heritage. Typical sounding rocket programs, such as the program at the University of Colorado's Laboratory for Atmospheric and Space Physics (PI: Tom Woods) where a team of undergraduate lead by a graduate student design, build and launch new instruments, are often proving grounds for next-generation instrument concepts. CubeSat programs also proving fertile ground for developing new instrument concepts, allowing heritage to be built for these instrument before they are integrated in satellite mission programs.

Beyond Undergraduate & Graduate Education: K-12 Education & Citizen Scientists

While the focus of most student instrument programs is the workforce pipeline at the undergraduate and graduate level, there are important examples of programs that bring these programs into formal K-12 classrooms and out to a broader group of "Citizen Scientists". For example, the Stanford Solar Center's SID Space Weather Monitor, an inexpensive ($50) instrument, can be installed by students and used at the local school. The instruments detect changes to the Earth's ionosphere caused by solar flares, hence linking space weather issues directly to students' environments. Students "buy in" to the project by building their own antenna, a simple structure costing little and taking a couple hours to assemble. Stanford provides a centralized data repository where students can exchange and discuss data. The result of the project is a worldwide, 450-site-and-growing collaboration of scientists, teachers, and students investigating the Sun's influence on the Earth's ionosphere, and is now expanding to include amateur astronomers.

As another example, NASA's THEMIS placed magnetometers in or near 13 rural schools across the country. The teachers at these and/or neighboring schools take part in long-term professional development around space science and magnetometer data, and the mission website provides yearly professional development opportunities and maintains the magnetometer data. Evaluation suggests that 57% of the teachers said that active participation in the project sparked student interest, and that students were strongly impacted by being part of an operating NASA mission. Teachers also reported science course enrollment increases. Several students reported changing their intended major to science after involvement in the program.

The Role of the Commercial Space Industry in Student Instrument Programs

The rise of the commercial space industry over the last five years has changed the terrain of opportunities for student instrument programs. A new generation of space vehicles capable of economically delivering payloads and researchers is coming on line. Vehicles under development by commercial suborbital companies, such as

Virgin Galactic, Blue Origin, Armadillo Aerospace, and XCOR Aerospace, will allow unprecedented access to the space environment, as well as a new way to engage scientists and students. These vehicles are expected to revolutionize space access by providing frequent, low-cost access to space and the capability to carry research and education crewmembers. The programs, ideally suited for student instrument programs, may provide a suborbital ride for a fraction of the cost of a sounding rocket and are targeting to increase the number of suborbital opportunities, by some estimates, by as 10-fold or more. There are now important government-industry partnerships in this area (e.g., NASA's CRuSR program) designed to accelerate this progress.

The commercial suborbital program and its associated researchers and educators are growing at a dramatic rate, as evidenced by the rapidly increasing participation at conferences such as the Next-Generation Suborbital Research Conference and the conferences put together by the Commercial Spaceflight Federation. These efforts are directly assessing student instrument programs as one of the key areas of growth for their industry, while at the same time, opening a pathway to increase access to space in a routine and affordable way.

The Importance of Mentoring in Student Instrument Programs

When looking at student instrument programs, the issue of mentoring models – who mentors and under what circumstances, as well as how and when professionals are involved – clearly emerged as the overriding factor contributing to success. Successful student instrument programs have a wide range of mentoring or training models in place. Some generalizations about mentoring in these widely differing programs can be drawn:

1. Mentors need not be professionals. While professional scientists and engineers provide exemplary role models, mentors can also range from experienced undergraduates to graduate students and postdocs. That said, the leadership, value and vision must come from the senior team members. Student mentoring can't be just 'pawned off' on junior team members.
2. Mentoring doesn't need to be one-on-one, though sufficient time needs to be dedicated on the part of the mentor to insure the program's educational success.
3. Compensating mentors for their efforts, even minimally, insures that they have sufficient time to keep the student instrument programs a priority.
4. Mentors work to strike a balance between guiding the students down a successful path and giving the students enough independence to allow the students to take ownership.
5. Student instrument programs can be a way for mentors to extend their own knowledge base and expertise in ways that enhance their own professional development.

Program Evaluation

It is clear that student instrument programs can be evaluated along a number of axes, some of them very familiar to educators and others less so. Many of the student instrument programs will be run primarily by PI scientists who have little background in educational evaluation and may see extensive evaluation as an onerous barrier that may be difficult for them to overcome. There is a need for help in the establishment of student instrument programs evaluation models and tools, as a way to facilitate effective evaluation of these programs. For larger programs, evaluation should be considered a legitimate and required cost to be covered by the program.

Certainly, the success of the student instrument programs in terms of some basic metrics familiar to most:

About the Instrument or Program:

- Did the instrument get built?
- Was data obtained? Was the data analyzed?
- Did papers get written?

About the Students:

- How many students were involved and for how long?
- What were their backgrounds?
- Assessment of group dynamics and team building during the program.
- Assessment of professional progress during the program, as well assessment of student attitudes towards science and engineering before and after participation in the program.

However, in order to truly evaluate the effectiveness of student instrument programs on the workforce, longitudinal tracking of participants for 3-5 years post-program (longer if possible) is an important component of the evaluation – critical for assessing student instrument programs impacts.

Community Support Infrastructure and Program Continuity

To ensure that the student instrument community thrives, leadership can be provided in a number of areas. First is in the area of visibility and support for student instrument programs. Historically it has been a challenge to create an ongoing program that supports the inherent nature of uncertainty in these projects. Student instrument programs involve trial and error learning, and identifying an appropriate scope for these programs where they are evaluated on a broad scale is important. Without consistent support from appropriate agencies, it is difficult to create a program with continuity and structure., although it is clear that models are beginning to emerge.

There are many institutions that run successful variations of student instrument programs. Every opportunity to bring them together to talk about what's working and where they need help is worthwhile. In addition, there is a consensus that finding a way to make exporting successful programs to institutions interested in pursing them would be beneficial to everyone, increasing the presence and role of universities in workforce training. Opportunities to share information also lead to greater coordination and leveraging of student instrument programs opportunities. Establishing connections and creating community among a broad range of institutions interested in student instrument programs, including NASA, NSF, commercial partners, university groups, etc. will increase communication between entities with the same goal.

Special emphasis should be placed on securing participation from Historically Black Colleges and Universities (HBCU), Minority-Serving Institutions (MSI), Hispanic-Serving Institutions (HSI), Tribal Colleges and Universities (TCU) and other colleges whose student populations are predominantly underrepresented minorities and communities in student instrument programs and their implementation. Studies show that the majority of underrepresented minorities in STEM areas graduate from these institutions. With the declining enrollment of US citizens in engineering and science graduate programs, recruitment and retention of underrepresented minorities is becoming increasingly important in the growth and production of the STEM workforce in the United States. This becomes particularly important, given the restrictions of the NASA workforce, in many cases, to only US citizens.

Challenges for Student Instrument Programs

Access to space remains the single most critical barrier for increasing the impact of student instrument programs. Launching is a key incentive to any group, providing closure, and driving the mission through the data analysis phase. Yet the rides are few and far between. Only one new Heliophysics rocket/balloon payload (UC-Berkeley's FOXI) was funded in FY10 as part of the NASA LCAS program, out of 10 proposals submitted. The Air Force is also behind in its launch windows for student programs, many of which are sitting on the shelf, waiting for an opportunity.

Some progress has been made, as NASA has incentivized its student instrument programs for satellite platforms for PI-lead missions. However, access to space would be substantially improved with the development and implementation of a standardized, robust system (such as the DoD ESPA ring adapter or CubeSat P-POD) for carrying secondary payloads on existing and planned launch vehicles. This would take advantage of the significant excess lift capacity that commonly exists and is already paid for in launch vehicle costs. In addition, increasing access to space through government/commercial partnerships (e.g., NASA's CRuSR program), as the commercial suborbital industry expands, is also seen as a critical step forward.

Providing a stable and sustainable terrain is a critical challenge that can be substantially alleviated through agency commitments and interagency coordination. Student instrument programs are not, relatively speaking, expensive. History has shown that when an agency makes a commitment for student instrument programs (e.g., NSF's support of CubeSat), the impact can be substantial. However, more often than not, student instrument programs are not seen as a funding priority, falling in the cracks between education programs and science programs. The result is that student instrument programs live on the edge within most agencies, funded when a program officer takes interest and defunded when a new program officer does not.

In addition to the funding of the student instruments themselves, some limited infrastructure could substantially improve the health of the student instrument program community. Community access to pooled best practices (e.g., mentoring models, program structure, etc.), evaluation tools, and other assets would strengthen the student instrument community, as well as provide support for institutions or individuals interested developing and implementing new programs.

Support for a wide variety of opportunities will allow participants to enter at levels that meet their needs, background, and experience. In addition, a broad range of opportunities allows a wide variety of institutions to participate, including community colleges, small liberal arts colleges, and minority-serving institutions. In a large university, there may be a range of student instrument programs, from specific facets of instrument design through fully realized suborbital platform with multiple instruments deployed. At smaller institutions, single suborbital programs and/or instrument development programs may be more accessible.

Summary of Recommendations

Student instrument programs should be encouraged throughout NASA, NSF and DoD.

These programs directly impact the workforce development in science and engineering that the United States has identified as a critical need. Government agencies, particularly because they currently control access to space, need to take the lead on ensuring the stability and sustainability of these important programs.

PIs proposing student instrument programs should be given wide latitude in defining the program, whose elements may include science, engineering and mission operation components, with an emphasis on the education impact of the effort.

Different educational settings require different types of student instrument programs – one size definitely does not fit all. In ideal settings, a progression of opportunities – from a single facet of instrument design to fully realized launches – creates scenarios where students develop educational maturity and experience. However, all student instrument programs are primarily educational opportunities and have an emphasis on educational outcomes at their core.

Scientists should be encouraged to develop inexpensive instruments that can be deployed or exported easily in a wide variety of education settings.

These kinds of student instrument programs require only a small amount of funding, but it needs leadership and vision from experienced scientists. Efforts should not just target 'the outstanding student who needs an extra challenge" but a broad range of students to grow the whole workforce. Most importantly, these programs are readily exportable to smaller institutions (e.g., community colleges, liberal arts schools, minority-serving institutions) and will have direct impact in increasing the diversity of our science and engineering workforce.

Access to space remains one of the most critical elements for sustaining student instrument programs.

Government agencies are encouraged to look broadly at ways to provide sustainable access to space, including expanding the suborbital launch opportunities within their control, as well as working to partner with the commercial suborbital industry.

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Data Assimilation for the Thermosphere and Ionosphere

Motivation: The future of space weather products and services for the ionosphere and thermosphere (IT) is in the development of global data assimilation schemes using coupled thermosphere ionosphere models and large amounts of diverse data. This is the same path that troposphere weather prediction has taken a few years back. Data assimilation in the IT system is required because of the impossibility to measure the forcing of the system with the necessary spatial and temporal resolution. The thermosphere and ionosphere are coupled so tightly that successful modeling of one is not possible without the other. A data assimilation scheme that makes use of both thermosphere and ionosphere measurements would provide great potential for better ionospheric specification and forecast and equally importantly, better interpretation of model data comparisons for better knowledge of the physics. At the same time it would open the way for specification and forecast of total neutral mass density and neutral winds which are necessary for tracking the ever increasing number of satellites and pieces of space debris and for calculating reentry orbits.

A successful data assimilation scheme for the thermosphere ionosphere system requires a well tested and validated coupled thermosphere ionosphere model and large amounts of data with known uncertainty (error) estimates. Ideally, the testing and validation process for the model and the data sets would take place in a near-operational environment.

There are several well tested coupled models of the thermosphere ionosphere system. The models have been used for more than 20 years and their capabilities and limitations are well known. With access to an ever increasing amount of real-time measurements one can develop testbeds for evaluating not just the models but in the future also the measurement biases of different instruments.

Schemes to automatically run the models in real-time using near-operational data bases, produce relevant plots, and display them in a web page for community comments and suggestions already exist.

What is needed:

1. Improve the present schemes to run models in real-time and provide real-time results to both the research community and to operational forecast centers.

2. Develop on the fly independent evaluation and verification procedures for models and data. Compare model results from different research assimilation schemes with global data sets and other available measurements.

3. Develop an operational data assimilation capability for the IT system. This is an important effort that will have to be eventually applied to all domains from the Sun to the bottom of the oceans. However, as opposed to the troposphere system which is chaotic and requires precise specification of the initial condition, the IT system is externally strongly forced by variations in the total energy input and its spatial distribution. Proper knowledge of the system inputs over a few days can make the initial condition irrelevant in terms of the induced uncertainty in the final state. This difference may make the optimum data assimilation schemes for forced systems very different from those developed for chaotic systems.

Investigations of Global Space Weather with GPS

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Overview

Space weather can pose serious threats to space-based and land-based technological systems, and many of the serious space weather effects are produced by ionospheric storms. The global distribution of ionospheric sensors is severely lacking, especially over the oceans and in remote, difficult to access areas (Africa, some parts of Australia and South America.) Currently many questions remain about influence of longitude, the offset of the geomagnetic and geographic poles, and the South American Anomaly on the development of total electron content (TEC) gradients, enhancements, and depletions. Near real-time, globally distributed measurements of TEC and scintillation parameters are needed to provide a comprehensive picture of the mechanisms that drive major space weather effects. Space weather is just one piece of the larger, complex geospace system. The measurements described here will provide information about the larger geospace environment, and will support a systems perspective to geospace.

I. Introduction

The field of Space Weather studies the effect of short-term variations which occur on the Sun and in the solar wind and which result in changes in the behavior of the coupled ionosphere/thermosphere system. Space weather can pose serious threats to space-based and land-based technological systems. An example of this was described by Doherty et al., 2004, when, during the 2003 October 29th and October 30th ionospheric storms, there was no vertical navigation service in the FAA's Wide Area Augmentation Service (WAAS) coverage area for more than 11 hours on both days. Space weather effects include: an increase in the atmospheric drag on satellites; an increase in ionospheric scintillations (which can cause perturbations in navigational signals and communications); errors in GPS and in VLF navigational systems; loss in HF communications; electrical power blackouts due to damaging currents induced in power grids; and increased risk of radiation exposure to astronauts. Ionospheric storms in particular are closely associated with geomagnetic storms and, as described by Buonsanto [1999], represent an extreme form of Space Weather.

Ionospheric storm phenomena that can introduce space weather effects include exceptionally large values of total electron content (TEC), which can introduce range errors; large spatial and temporal gradients in the TEC, which can introduce differential range errors; and small scale density irregularities which can cause scintillation and/or loss of ability to track signals. An example of this is shown in Fig. 1, where the large TEC gradients associated with the 2003 November 20 ionospheric storm produced rapid variations of TEC which translated to large and rapidly changing range errors for GPS over both Washington, DC and Pittsburgh PA.

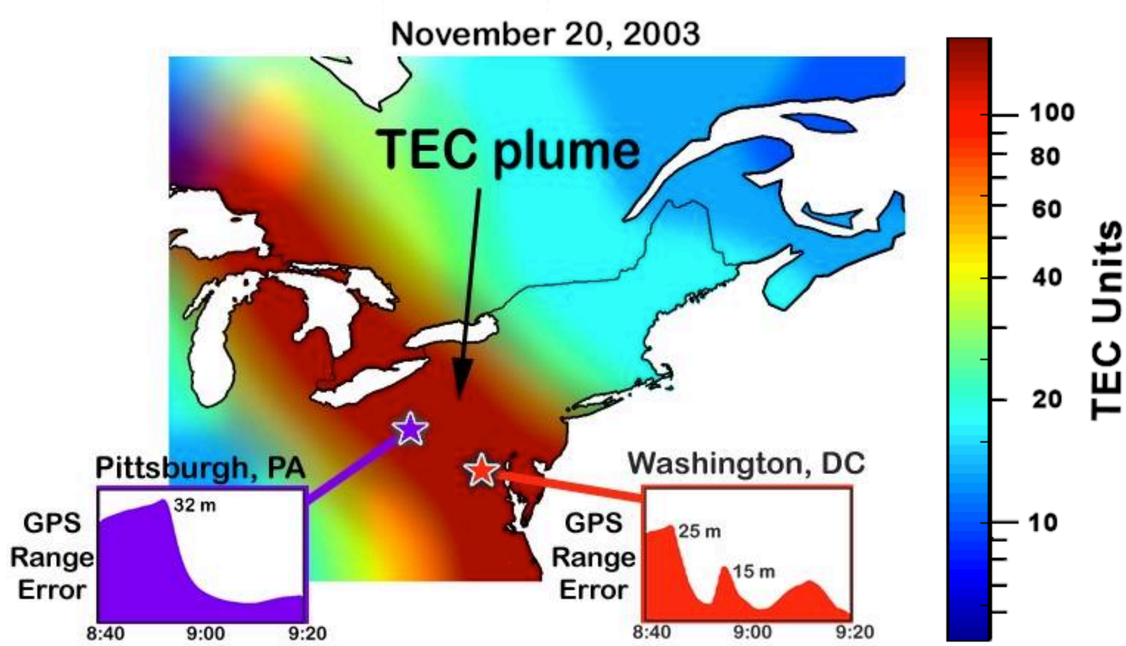

Figure 1. Contour plot of Northeastern U.S.A. showing range errors due to ionospheric delay variations using GPS (courtesy of Mannucci, JPL/NASA)

Many of the significant space weather events that have been reported are from N. American observations of storm enhanced density (SED) (Foster, 1993; Foster et al., 2002). Often associated with SED are large TEC gradients (Coster and Foster, 2007) and small-scale irregularities (Ledvina et al, 2002). One reason for the focus on North America is that during the last solar maximum (2000-2003) only the US had a dense enough network of GPS receivers to fully view SED plumes. Recently, SED plumes have been reported in Europe (Yizengaw, et al., 2006) and in Japan (Maruyama, 2006). Many aspects of the SED feature appear to be magnetically conjugate (Foster and Rideout, 2006), although there is considerably less data coverage for observing such effects over the oceans and in the southern hemisphere (South America, Australia, and especially Africa). Space weather effects not associated with SED include the formation of many types of irregularities, including those associated with traveling ionospheric disturbances (TIDs) (Kelley and Fukao, 1991, Saito et al., 2002), midlatitude spread-F (Bowman, 1990), and other mechanisms. Solar radio bursts are another example of space weather. The Solar Radio Burst on December 6, 2006 produced a dramatic reduction in the reception of GPS signals on the sunlit side of the Earth during the 10 minutes associated with the peak of the radio burst (Cerruti, et al., 2008).

II. Science Questions

As our society becomes increasingly dependent on technological systems such as the Global Positioning System (GPS), the ability to monitor and predict space weather in the near real-time is required. Certain critical applications such as railway control, highway traffic management, emergency response, commercial aviation, and marine navigation require high precision positioning. As a consequence, these applications require real-time knowledge of current and predicted space weather effects.

To achieve this goal, a number of science questions need to be addressed. For example, what is the difference in the formation of SED in the different hemispheres and as a function of longitude? From analysis of the current data sets, there appears to be a preferential longitude for the formation of SED (Coster et al., 2007, Yizengaw et al., 2008) that may be related to the offset of the geographic and geomagnetic poles in the North American continent. Recent studies indicate that this offset has important consequences for the development of SED in the American sector (Foster and Coster, 2007). Another question is what is the influence of the South Atlantic Anomaly (SAA), an area of weakened geomagnetic field that lies over Brazil and part of the Atlantic Ocean, on the development and formation of space weather effects in both the American and African longitude sectors. Satellite observations (Hei et al., 2005) indicate that the ionosphere over Africa behaves very differently than the ionosphere over South America.

III. Required Observations

Currently global maps of TEC show large regions void of data over the oceans, even when COSMIC occultation data are included. This is illustrated in Figure 2, which represents an hour average of all TEC measurements from both the global network of GPS receivers and from COSMIC TEC measurements (represented by the letter "C".) Areas of white indicate areas of no data in this figure. This lack of data makes global space weather prediction/interpretation difficult. Just from observing this figure, one can see an area over Florida of slightly increased TEC, during a nighttime period of 3:00-4:00 UT (22:00-23:00 LT). This also has a clear connection across the ocean to the enhancement shown at the western tip of Africa, which is in the post-midnight local time sector. Is this enhancement related to the physics associated with the SAA?

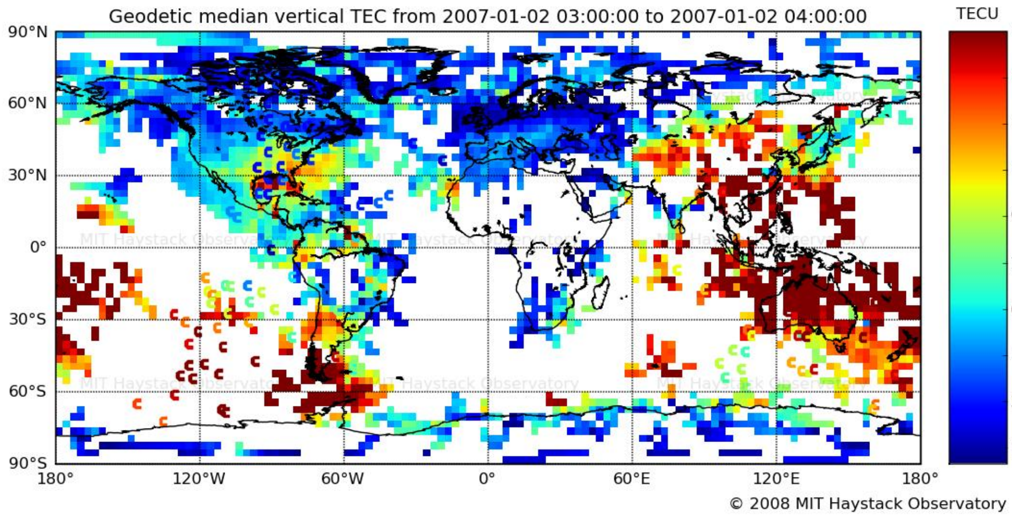

Figure 2. Global TEC map combining data from COSMIC and from the global network of GPS receivers for 2007-01-02. All data between 03:00:00-04:00:00 UT included.

IV. Required Instrumentation

To fully address the space weather problem, we should have the goal of real-time characterization of the global ionosphere as a standard product. This characterization will rely heavily on data from GPS measurements, but it will be enhanced by the real-time measurements from other sensors. To meet this goal, there is a requirement for real-time or near real-time observations from multiple platforms distributed uniformly over the globe. There is also a requirement to provide easy and open access to the data in standardized data formats and from easily identifiable and well-known data collection sites. Issues such as cost of instrumentation, power requirements, and connectivity must be addressed. These are all achievable within the next decade, especially with GNSS instrumentation such as GPS. The concept being described is that of "Distributed Arrays of Small Instruments for Space Science (DASI)." The last Decadal Survey of Solar and Space Physics (National Academy of Sciences, 2003) encouraged the deployment and utilization of distributed arrays of small instruments (DASI) to further space physics research.

In recent years, GPS has become recognized as one of the premier remote sensing tools to monitor space weather events. By measuring the differential delay between GPS signals on two frequencies, the total electron content (TEC) can be measured along the line of sight between the receiver and the satellite. By combining TEC measurements from the worldwide receiver network, changes in the TEC distributions can be monitored along with the development of TEC gradients involved in serious space weather. In addition, by looking at TEC fluctuations, or by tracking the instances of "loss of lock," GPS data can also be used to monitor ionospheric scintillation, another serious space weather phenomenon.

In the last decade, considerable understanding of space weather phenomena has been achieved by interpretation of global TEC maps. In a groundbreaking paper, Foster et al. [2002] linked narrow plumes seen in midlatitude GPS TEC observations as measured from the ground with plasmaspheric plumes as seen from 8 Earth radii by NASA's Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) satellite. This last observation clearly demonstrated that a dense network of ground-based receivers can play a significant role in measuring the coupling between the ionosphere and the magnetosphere. A global network of GPS receivers can, and does, provide data that enables a system-science approach to the coupled, complex geospace system.

Especially during large geomagnetic storms, single ground-based GPS receivers have a distinct advantage over satellite-based occultation systems such as COSMIC because no assumptions of uniform distribution are the made in analysis. Filling the gaps in TEC information over the oceans and over all of the continents (Africa, South America) will provide the necessary information to fully study space weather effects and to study the coupling between different atmospheric regions. Another example of how global networks of GPS receivers enable system-science is demonstrated in the recently observed ionospheric signatures following sudden stratospheric warming events [Goncharenko, et al., 2010a; Goncharenko et al., 2010b]. This work provided clear evidence of the coupling between the stratosphere and the ionosphere. Global networks of GPS receivers can provide observations of travelling ionospheric disturbance associated with geomagnetic storms and tsunamis [Occhipinti, et al., 2008, Galvan, et al., 2010] . With GPS modernization, there are currently 8 GPS satellites broadcasting civilian signals on 2 or more frequencies. These new dual-frequency civilian signals enable ionospheric measurements on moving platforms for scientific purposes. This was very difficult to achieve prior to modernization. In addition, new low-cost, lower power GPS receivers are now available [Humphries, 2008; O'Hanlon, 2009]. These low cost receivers can be used to augment data output from the African sub-continent and, when incorporated on low cost buoys, they can provide data over the oceans. In the future, additional GNSS signals such as GLONASS, COMPASS, and EGNOS can be incorporated into the receivers and used for analysis. Incorporating these new GNSS signals with GPS signals will provide higher accuracy and more reliable information in all environments.

What is needed is a large global array of scientific instruments capable of providing high temporal and spatial information about the ionosphere in near real-time. New low-cost, lo-power GPS receivers are available and can be made to work in the ocean environment and in remote hard to get to regions.

V. Broader Impacts

In addition to space weather information, the science products enabled by low-cost GPS receivers will lead to several direct societal benefits. High precision GPS positioning information on the oceans can be used to improve severe storm warnings and space weather forecasts, and to augment tsunami-warning systems. Offshore sea level measurements will allow us to determine the relative contributions of winds and waves to sea level variations and improve the existing storm surge models.

VI. Summary

Society cannot become overly reliant on technology without an awareness and understanding of the effects of future space weather disruptions. As technology advances, societies of tomorrow are expected to only increase their need for highly accurate communication and navigation systems. These systems are vunerable to space weather and yet many of these systems are critical to our ability to respond to other emergencies. Most space weather effects are global in nature. For society to properly address them, real-time, global information will be required.

To achieve these goals, problems that must be overcome include:

- Collecting space weather data over oceans and in remote, difficult to access locations
- Reliable and relatively inexpensive global communication links
- Real-time data transfer and access
- Establishment of open, free, easily accessible databases
- Data stored in standardized, common formats

Regional TEC maps have provided a system-level understanding of many space weather effects. Regional TEC maps have also provided a deeper understanding of the coupling between different regions (the ionosphere and the magnetosphere; the ionosphere and the stratosphere). In the coming decade, the goal should be to provide global near-real time TEC maps.

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The International Space Weather Initiative (ISWI)

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Abstract

The International Heliophysical Year (IHY) provided a successful model for the deployment of arrays of small scientific instruments in new and scientifically interesting geographic locations, and encourages outreach. The new International Space Weather Initiative (ISWI) is designed to build on this momentum to promote the observation, understanding, and prediction of space weather phenomena, and to communicate the scientific results to the public. International initiatives such as ISWI provide the communication links with developing nations to enable the instrument deployment. Networks of ground-based observations can substantially enhance the return from magnetosphere-ionosphere-thermosphere space missions. The need to extend and enhance the density of ground-based instrument arrays remains a high priority.

Introduction

The International Heliophysical Year (IHY) was an international program of scientific collaboration involving thousands of scientists from more than 70 countries, which was conducted from February 2007 to February 2009. Along with programs of research, outreach, and IGY history preservation, activities included the deployment of new instrumentation arrays especially in developing countries. A detailed account of all IHY activities is reported in the book The International Heliophysical Year: Putting the "I" in IHY, by Barbara J. Thompson, et al (2009).

It was recognized early in the planning of the IHY that the understanding of the global ionosphere and its linkage to the near-Earth space environment was limited by the lack of observations in key geographical areas, e.g. near the magnetic dipole equator and in other longitude sectors. A good example is the African longitude sector, which has the longest continuous stretch of landmass under the geomagnetic equator. To address this need, a series of workshops were held to facilitate collaborations between research scientists in scientifically interesting geographic locations, and researchers with the expertise to build scientific instrumentation. From these meetings scientific teams emerged. Each team consisted of a lead scientist who provided the instruments or fabrication plans for instruments in the array. Support for local scientists, facilities and data acquisition was provided by the host nation. All scientists participate in the analysis of the data from the instrument array. As a result of this program, scientists from many countries now participate in the instrument operation, data collection, analysis, and publication of scientific results, working at the forefront of science research.

The instrument deployment program was one of the major successes of the IHY. Arrays of small instruments such as magnetometers to measure fluctuations in Earth's magnetic field to estimate equatorial electric fields, radio antennas to observe solar coronal mass ejections, GPS receivers, VLF radio receivers, and all-sky cameras to observe the ionosphere, and muon particle detectors to observe

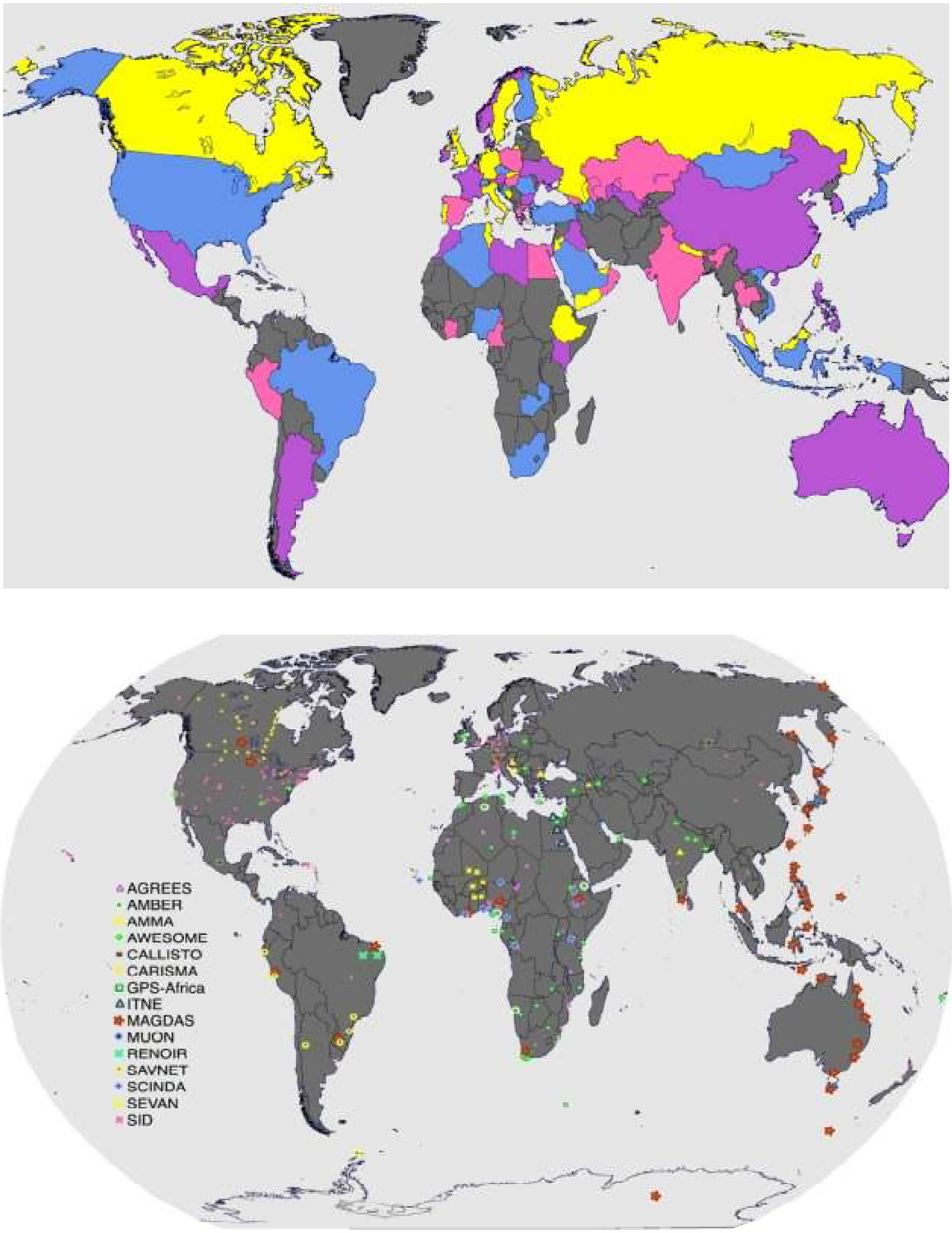

Figure 1 Over 70 countries are participating in the ISWI with national organizing committees, and almost 1000 instruments are currently cooperating in the program.

energetic particles were installed around the world. These arrays continue to provide global measurements of heliophysics phenomena.

An interesting side benefit of the instrument program was the seeding of heliophysics research groups in universities where there had been none before, and the strengthening of existing heliophysics research groups where new instruments were installed.

Building on this concept, in February 2009 the International Space Weather Initiative (ISWI) was proposed to the Science and Technology Subcommittee (STSC) of the United Nations. The program will continue the study of universal processes in the solar system that affect the interplanetary and terrestrial environments, and to continue to coordinate the deployment and operation of new and existing instrument arrays aimed at understanding the impacts of Space Weather on Earth and the near-Earth environment. The ISWI was adopted by the Committee for the Peaceful Uses of Outer Space (COPUOS) in June 2009, and approved by the UN General Assembly in the Fall of 2009. In addition to the United Nations, ISWI is supported by the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and the International Committee on Global Navigation Satellite Systems (ICG). Additional information on the ISWI is available at http://iswi-secretariat.org.

In this paper, we describe the goals and objectives of the ISWI program as it is currently envisioned.

Goals and Objectives

The ISWI will help develop the scientific insight necessary to understand the physical relationships inherent in space weather, to reconstruct and forecast near-Earth space weather, and to communicate this knowledge to scientists and to the general public. This will be accomplished by (1) continuing to deploy new instrumentation, (2) developing data analysis processes, (3) developing predictive models using data from the instrument arrays, and (4) continuing to promote knowledge of heliophysics through education and public outreach.

Instrument Array Development

The ISWI will continue to expand and deploy new and existing instrument arrays following the successful model demonstrated during the IHY. The basic principles of this model are simple. Each instrument team is led by a single scientist. The lead scientist or principle investigator, funded by his/her country, provides instrumentation (or fabrication plans) and data distribution. In a few cases, where resources allow, the hosting country will pay for the instrument. The host country provides the workforce, facilities, and operational support necessary to operate the instrument. This is typically at a local university or government laboratory. Host scientists become part of science team. All data and data analysis activity is shared within the science team, and all scientists participate in publications and scientific meetings where possible.

The current list of instrument providers is shown in Table 1. This list is not expected to remain static. Through workshops and other means, the ISWI will actively seek to identify additional instruments, and instrument providers that could benefit from the ISWI process, as well as new instrument hosts.

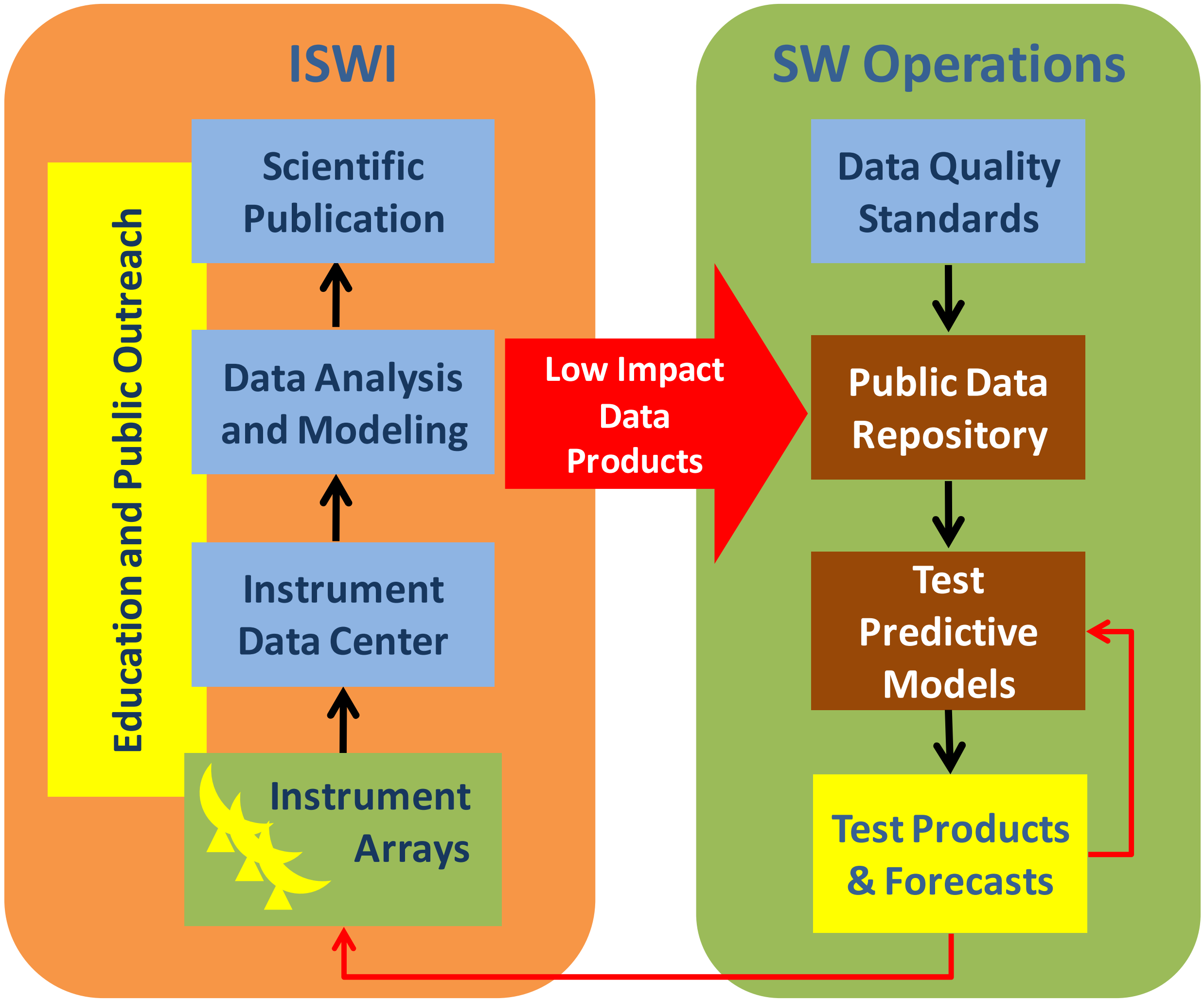

Figure 2 The instruments deployed in the ISWI provide data useful for Space Weather research and for forecasting.

Data Analysis

The ISWI program will promote the coordination and accessibility of instrument array data via NASA's Heliophysics virtual observatories (VxOs). The ISWI will also coordinate instrument teams' efforts to put data in a form useful for multi-instrument analysis and input into physical models of heliophysics processes. These data will be used for both retrospective analysis aimed at physical understanding of space weather, and for predictive models to predict future space weather conditions.

To be useful for space weather prediction, data must be available in near real-time. However, today internet connections are intermittent or slow in many locations in the developing world, making near real-time data return impossible. Eventually, as internet connectivity improves, these data will be made available in near real-time in a form where they can be ingested into predictive models. In the near term, other strategies like installing satellite communication link, data transfer only during selected time periods, or on recorded media like DVDs and tapes are adequate for archiving the data for retrospective scientific studies of space weather events and development of physical models.

Data from the instrument arrays will be made accessible directly from public data archives or searchable along with other heliophysics data from various Heliophysics VxOs: the Virtual Ionosphere, Thermosphere and Mesosphere Observatory (http://vitmo.jhuapl.edu), the Virtual Wave Observatory (http://vwo.nasa.gov), the Virtual Magnetospheric Observatory (http://vmo.nasa.gov), the Virtual Heliospheric Observatory (http://vho.nasa.gov/), and the Virtual Solar Observatory (http://sdac.virtualsolar.org/cgi/search). This will make data from ISWI instruments available and productively used in conjunction with other heliophysics data by the broader community of researchers.

Supporting Magnetosphere-Ionosphere-Thermosphere Science

ISWI instrument arrays can support a variety of magnetosphere-ionosphere-thermosphere studies by providing "ground-truth" observations. These observations can be used to pose lower boundary (thermospheric and ionospheric) conditions needed in magnetospheric models or in coordinated multi-instrument campaign studies. The instruments that measure airglow and optical emissions in the ionosphere / thermosphere (RENOIR and OMTIs) will provide direct information about gravity wave forcing of the I-T system, as well as ionospheric disturbances, plumes, and large-scale instabilities. For example, new instrumentation deployed in Africa has already demonstrated that the likelihood of hazardous ionospheric irregularities that impact satellite communication are much more prevalent in this longitude sector, due to the particular configuration of the Earth's magnetic field. , In addition, I-T missions will often fly directly through the volumes that are "imaged" by the GPS networks (2, 5, and 10), which can then provide important context for analyzing the satellite measurements. They also provide "space truth" for the inversions of satellite remote-sensing data. The AWESOME VLF receivers will aid in connecting space observations of lightning to ground-based observations of lightning intensities, locations, and other characteristics, helping to constrain both the microphysics of wave propagation in the low-latitude ionosphere, the effects of lightning on the ionosphere-thermosphere, and the effects of lightning and large weather systems in possibly seeding ionospheric instabilities. Finally, the magnetic field measurements planned for ISWI (AMBER and MAGDAS) will provide strong inputs to models of magnetic micropulsations (ULF waves), the equatorial electrojet, E- and F-region dynamo and penetration electric fields (with SAVNET), sub-auroral polarization stream, storm-enhanced density, and other current systems (including magnetospheric-driven effects) that will help constrain models for investigating magnetosphere-ionosphere coupling processes.

Table 1 ISWI instrument arrays are from several countries, and cover a range of science.

ID	INSTRUMENT	Lead Scientist	Country	Objective
1	Scintillation Network Decision Aid (SCINDA)	K. Groves keith.groves@hanscom.af.mil (Hanscom AFRL)	USA	Study equatorial ionospheric disturbances to aid in the specification and prediction of communications degradation due to ionospheric scintillation in the Earth's equatorial region
2	Ionospheric Tomography Network of Egypt (ITNE) Coherent Ionospheric Doppler Receiver (CIDR)	A. Mahrous amahrous@helwan.edu.eg (Helwan University) T. Garner garner@arlut.utexas.edu (University of Texas)	USA	To tomographically reconstruct the ionosphere and to provide input to data assimilation models
3	Atmospheric Weather Education System for Observation and Modeling of Effects (AWESOME) and Sudden Ionospheric Disturbance monitor (SID)	U. Inan inan@stanford.edu M. Cohen mcohen@stanford.edu D. Scherrer deborah@solar2.stanford.edu (Stanford University)	USA	Lightning, sprites, elves, relation to terrestrial gamma ray flashes, whistler induced electron precipitation, conjugate studies. Education and public outreach.
4	Remote Equatorial Nighttime Observatory for Ionospheric Regions (RENOIR)	J. Makela jmakela@illinois.edu (University of Illinois)	USA	Study the equatorial/low-latitude ionosphere/thermosphere system, its response to storms, and the irregularities that can be present on a daily basis
5	African GPS Receivers for Equatorial Electrodynamics Studies (AGREES)	E. Yizengaw (Boston College) ekassie@igpp.ucla.edu M. Moldwin (University Mich)	USA	Understand unique structures in equatorial ionosphere, low/mid latitude plasma production, effect of ionospheric and plasmaspheric irregularities on communications
6	African Meridian B-field Education and Research (AMBER)	M. Moldwin (University Mich) mmoldwin@igpp.ucla.edu E. Yizengaw (Boston College)	USA	Understand low latitude electrodynamics, ULF pulsations, effect of Pc5 ULF on MeV electron population in inner radiation belts

ID	INSTRUMENT	LeadScientist	Country	Objective
7	Compound Astronomical Low-cost Low-frequency Instrument for Spectroscopy and Transportable Observatory (CALLISTO)	A.Benz benz@astro.phys.ethz.ch C. Monstein monstein@astro.phys.ethz.ch (ETH)	Switzerland	Study of radio flares caused by solar activity in view of space weather and climate change
8	South Atlantic Very Low frequency Network (SAVNET)	J.-P. Raulin raulin@craam.mackenzie.br (University Presbiteriana)	Brazil	Study of the SAMA region at low ionospheric altitudes and its structure and dynamics during geomagnetic perturbations
9	Magnetic Data Acquisition System (MAGDAS)	K. Yumoto yumoto@serc.kyushu-u.ac.jp (Kyushu University)	Japan	Study of dynamics of geospace plasma changes during magnetic storms and auroral substorms, the electromagnetic response of iono-magnetosphere to various solar wind changes, and the penetration and propagation mechanisms of DP2-ULF range disturbances
10	African Dual Frequency GPS Network	C. Amory-Mazaudier christine.amory@lpp.polytechnique.fr (CETP/CNRS)	France	To increase the number of real-time dual-frequency GPS stations worldwide for the study of ionospheric variability, response of the ionospheric total electron content (TEC) during geomagnetic storms over the African sector

ID	INSTRUMENT	LeadScientist	Country	Objective
11	Space Environmental Viewing and Analysis Network (SEVAN)	A.Chillingarian chili@aragats.am (Aragats University)	Armenia	A network of particle detectors that aims to improve fundamental research of the particle acceleration in the vicinity of the Sun and the space environment, as well as to provide forewarnings of dangerous consequences of space storms
12	Global Muon Detector Network (GMDN)	K. Munakata kmuna00@shinshu-u.ac.jp (Shinsu University)	Japan	To identify the precursory decrease of cosmic ray intensity that takes place more than one day prior to the Earth-arrival of shock driven by an interplanetary coronal mass ejection
13	Flare Monitoring Telescopes (FMT) under the Continuous H-alpha Imaging Network (CHAIN)	S. UeNo ueno@kwasan.kyoto-u.ac.jp K. Shibata (Kyoto University)	Japan	Time variation and 3D velocity field of solar activity, flares, filament eruptions and shock waves (Moreton waves) by using multi-wavelength H-alpha images of the full-disk Sun.
14	Optical Mesosphere Thermosphere Imagers (OMTIs)	K. Shiokawa shiokawa@stelab.nagoya-u.ac.jp (Nagoya University)	Japan	Dynamics of the upper atmosphere through nocturnal airglow emissions http://stdb2.stelab.nagoya-u.ac.jp/omti/index.html

Training, Education, and Outreach

During the IHY space science schools in US, China, India, Brazil, and Nigeria provided training to hundreds of graduate students and new researchers. The ISWI will continue providing support for space science schools. The ISWI will continue to promote space science and the inclusion of space science curricula in universities and graduate schools. This has been most effective when combined with the installation of instrumentation at the university.

The ISWI will continue to support public outreach projects and field trips such as solar eclipse observation expeditions. It is essential to communicate the excitement, the beauty, and the relevance of heliophysics science to students and scientists from other disciplines, and to the public at large. We will continue to develop public outreach materials unique to the ISWI, and coordinate the distribution of these materials through individual contacts, scientific and educational meetings, and outreach workshops.

Summary and Conclusions

The ISWI will continue a portion of the IHY program, providing a forum for the formation of scientific collaborations between instrument providers and instrument hosts. The need to expand the ground-based networks in different longitude sectors and in geophysically import regions remains a critical need. Initially data will be used primarily for understanding the physical processes important for space weather phenomena. Later, ISWI will move toward near real-time data availability as internet connectivity improves, allowing data ingest for predictive modeling. A robust program of outreach is envisioned, with a continuation of the space science schools, support for university space science curricula, and a public outreach program.

The cost for this program is of order $0.5-1.0 M/yr. All of the funding goes to support new US scientists, US instruments, data analysis, and data availability within the US. All foreign investigators and foreign instruments are supported by their own funding agencies, though data is made available internationally. An endorsement from the Decadal Committee for this important project will assure that future ITM missions are properly supported with ground observations from relevant locations internationally with a very modest investment from the US science budget.

Understanding Magnetic Storage, Reconnection, and CME Initiation

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1 SUMMARY

The fundamental structures in the inner corona, those within a solar radius from the visible limb, can only be studied with visible light images of the corona taken during a total solar eclipse at the present time. Existing EUV imagers, like those on SDO, can capture extremely fine scales but only in selected ranges of temperature. Current space-based coronagraphs can image the region > 1.5 Rsun from the limb with relatively low spatial resolution (see Table 1). During a total solar eclipse, high resolution images can be taken from the ground (Figure 1), but natural eclipses typically occur only once per year for 2-6 minutes. Ground-based coronagraphs are extremely useful, but cannot provide the continuous observations needed to fully understand the CME energy build-up, initiation, and coronal relaxation process.

It is now technologically feasible to build a coronagraph that can rival the image quality of eclipse instruments but without the duty-cycle restrictions of an eclipse. A standard coronagraph with an external occulter mounted on a boom can provide low noise, eclipse-quality visible light images (*1-2 arcsec spatial resolution*) of the very inner corona ($1.02 - 4R_\odot$) with high cadence (*<1 minute*) from L1 to study the formation and initiation of CMEs, the genesis of the solar wind, and the fine scale magnetic field morphology of the corona.

Table 1 Existing coronagraphs provide relatively low resolution images of the corona.

Instrument	FOV [Rsun]	Resolution [arcsec/pix]
SOHO/C2	2.5 - 6.0	11.4
SOHO/C3	3-32	56
STEREO/COR1	1.4 - 4.0	7.4
STEREO/COR2	2.5 - 10.0	13.2
Mauna Loa Mk IV	1.14 - 2.86	6

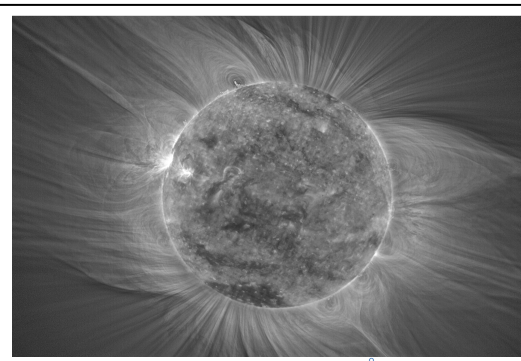


Figure 1 Composite of an EIT 171 Å and a visible light eclipse image. It is an example of the type of images that could (along with an *SDO*/AIA-like imager) be provided on a 24hr 365day basis instead of once a year. (*eclipse image courtesy of M. Druckmueller & P. Aniol*).

2 KEY SCIENCE QUESTIONS

The Sun's white light corona is visible only during a total eclipse or in a coronagraph. Its K-coronal component, formed by Thomson scattering of photospheric radiation by free coronal electrons dominates the F-component (due to scattering by dust) and E-component (due to line emission) at low altitudes. The early successes of externally occulted coronagraphs observing the K-corona led to a quasi-continuous space based coverage from the 1970's with S-052 on Skylab to the present with SECCHI on STEREO. The string of space based coronagraphs has done a marvelous job monitoring the *large-scale* structure of the white light corona, especially in understanding coronal mass ejections

(CMEs). But the fine structure in the corona that is readily visible during an eclipse is not visible in the current crop of space based instruments.

At the same time, it is becoming apparent that important clues about two fundamental problems in modern heliophysics, the formation of CMEs and the evolution of coronal transient phenomena, lie in the small scales of the corona. The inner corona, from the surface to 1 Rsun, is the region where coronal mass ejections originate, and observations of this region are essential for answering the question: *How are CMEs initiated?*

Physical models of the CME process are necessary to move forward on realistic modeling, and long term forecasting of solar activity. However it is impossible to distinguish between competing models unless high resolution white-light images are obtained. EUV images typically image a less than 1-10% of the corona (filling factors typically <<0.1). In white light coronagraph images, as opposed to EUV images, the observed emission is due to all electrons, regardless of temperature. If we are to understand where and how the initial reconnection occurs, we must observe the full corona to determine the sequence of events leading to eruption.

2.1 Primary Observations

Eclipses are too rare and too short-lived, and ground coronagraphs have insufficient duty cycle to allow observations to determine the initiation mechanism for CMEs. Breakthrough science can come from an externally occulted coronagraph with the occulter located 500 meters in front of the entrance aperture. This High resolution COROnagraph (HICOR) will *obtain the highest resolution (1-2 arcsec/pixel) and highest cadence (< 1 min)movies of the inner corona of any coronagraph ever flown* (Figure 5). The images will be comparable to the rare ground-based observations of natural eclipses (Figures 2-4), but with much higher cadence, and signal to noise ratio.

Primary Author	Critical Observation
Antiochos (Breakout)	Quadrapolar field with initial reconnection above the cavity causes a flux rope to form and be ejected, no pre-existing flux rope
Forbes, Mikic (Flux Addition)	Reconnection below a pre-existing flux rope repetitively adds additional flux until a state of non-equilibrium is reached
Moore (Tether Cutting)	Reconnection below the cavity removes the overlying field that keeps the pre-existing flux rope in static equilibrium
Gibson (Kink Instability)	No reconnection is involved in the initiation, a pre-existing flux rope become kink unstable
Wolfson (Mass Loading)	The critical signature is the presence of a large mass in the corona before eruption, and the downfall of most of this mass during eruption

It is now clear that many CMEs exhibit a flux rope structure in the coronagraph FOVs but the origins of this helical structure remain controversial. Although the majority of CME initiation models result in the ejection of a fluxrope, they cannot agree on how and when the structure forms. It can form during the eruption through reconnection above with the surrounding field (Antiochos breakout model), it may preexist and drive the eruption through ideal MHD plasma instabilities such as the kink and torus instabilities (as in the model by Gibson), or the flux rope may grow by reconnection below the flux rope until it erupts (Forbes, Moore, and Mikic models). The energy for the eruption may come from the magnetic stresses in the surrounding field (all models above), mass loading (Wolfson models), or some combination of both.

2.2 Collaborating Observations

An EUV imager is required to observe the site of the eruption at the surface of the Sun which is hidden behind the occulter. This imager would have a FOV which is nearly full-disk and extends up to >2 Rsun to provide overlap with the coronagraph FOV.

Davila and Reginald have pioneered a new observing technique to obtain electron temperature, and flow velocity from white light eclipse images. Results of several prototype observations during eclipses have been reported in the literature. This diagnostic capability can be added by simply adding filter positions to the filter wheel. The resulting diagnostic information would allow the observation of hot reconnection regions high in the corona where the emission measure is too low to be seen in EUV images. In addition, the velocity information would provide global maps of the solar wind speed near the Sun.

High energy imaging (X-ray, and Gamma-ray) could be added to study the development of the flare, and associated SEPs. A separate submission by Lin et al describes the high energy science.

The optimum combination and priority of the observations should be the subject of a Science and Technology Definition Team.

3 ESTIMATED COST

The optical design for this high-resolution coronagraph, HICOR, is a Lyot coronagraph with 15 cm entrance aperture. A filter wheel allows the observation of polarized brightness (pB) or visible line emission (e.g. Fe XIV), and a pair of buttable 4k x 4k provide an imaging area which covers half of the inner corona from 1.02 to 4.5 Rsun. The coronagraph could be off-pointed to obtain images in the more distant corona if desired, for example when Solar Probe or Solar Orbiter pass through perihelion.

Due to vignetting of the entrance aperture by the occulter, the resolution in the inner FOV depends on the distance to the occulter. A distance of 500 m provides 2 arcsec imaging even near the edge of the occulter. It is unlikely that this separation can be provided by a mechanical boom, therefore a second spacecraft carrying the occulter (and possibly some full disk imaging instruments) would be required. The technology for control of this 2-spacecraft formation is fairly well known, but has not been demonstrated in realistic simulations on the ground, or in space. PROBA-3, an ESA technology demonstration mission, will be flown in 2017. PROBA-3 will therefore act as a pathfinder for the HICOR mission. A reasonable development program would likely cost on the order of $10M based on the technology demonstration costs for Solar Probe. The cost of the spacecraft and instruments would be on the order of $700M. There are fewer instruments than SDO, but the complexity of two spacecraft, and the formation flying control would likely offset that difference.

The best place to position this coronagraph is at the Lagrange point, L1. There the disturbance forces are minimized, and the potential for backscatter from the Earth/Moon system is minimized. A launch vehicle to put two spacecraft into orbit at L1 is estimated to be of order $200M.

Operation costs are less well known. A guess would be of order $15M/year including DSN. There has been very little thought on the operations concept, and no formal cost estimate prepared however.

4 RELEVANCE TO THE DECADAL SURVEY

Understanding solar activity, of which the CME initiation process is a significant part, is a high priority within the Heliophysics community, and one of the most important scientific questions in Heliophysics. CMEs are one of the most dramatic and important aspects of solar activity, and they are responsible for many of the space weather phenomena observed within the heliosphere. This study will reveal new aspects of fundamental processes such as reconnection, flux rope formation and structure, and ideal instabilities in the corona. In addition to the fundamental science, this project would provide much needed information for the improvement of long-term space weather prediction providing significant societal benefits.

The instrument and spacecraft technology is currently available. Formation flying has been studied in the laboratory, and systems for spacecraft control to the accuracy needed have been identified. Additional testing of these systems in a more realistic space environment is needed to demonstrate this technology for spaceflight use. PROBA-3 will provide a pathfinder for this mission, and raise the TRL of formation flying technology prior to the development of HICOR.

Space weather research is rapidly becoming an international discipline. ESA has recently established a Space Situational Awareness center near Madrid, and the United Nations International Space Weather Initiative (ISWI) is a consortium of scientists from more than 70 countries working to make ground based space weather data available in new and interesting geographical locations.

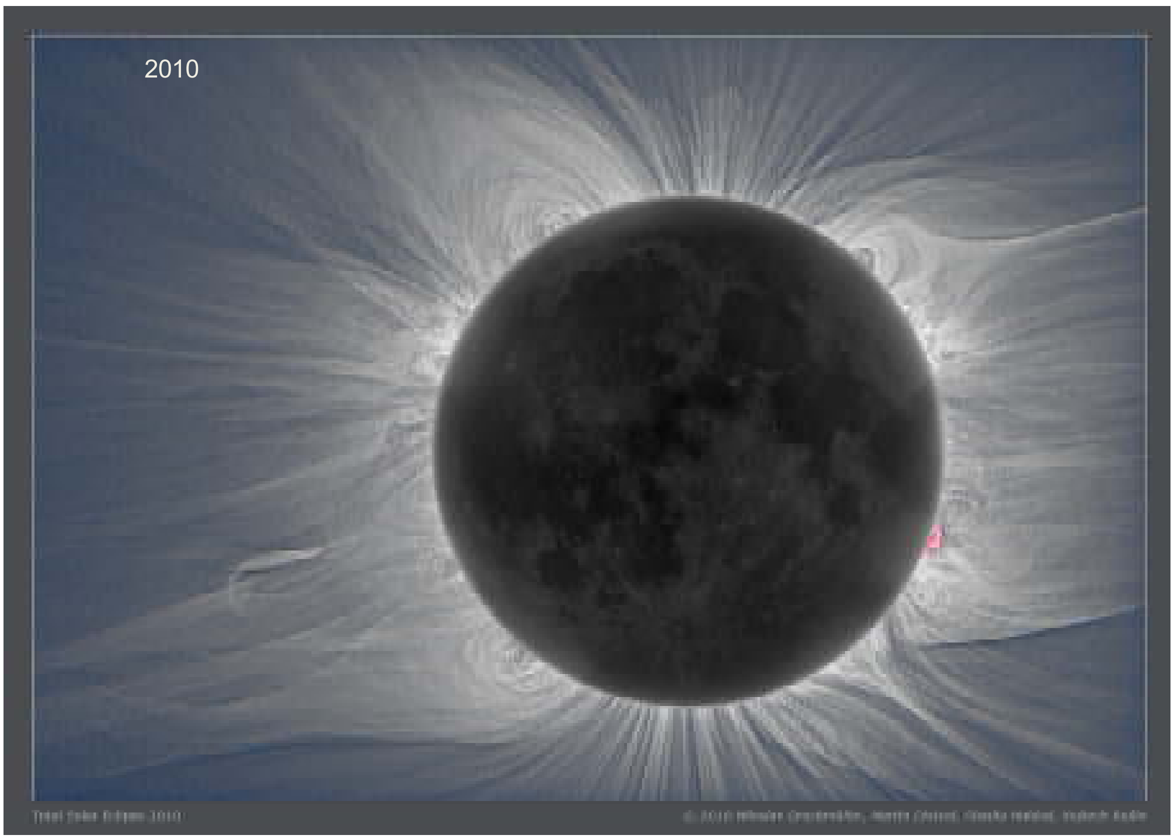


Figure 2. Image of the corona taken during the total solar eclipse in 2010 demonstrates that fine scale structure can be seen in the visible light corona, and that these structures trace the magnetic field of the Sun. A time sequence of these images would provide the data necessary to observe the energy storage process in the corona, and the subsequent reconnection and CME. These observations will provide new information on the conditions in the particle acceleration region near the Sun.

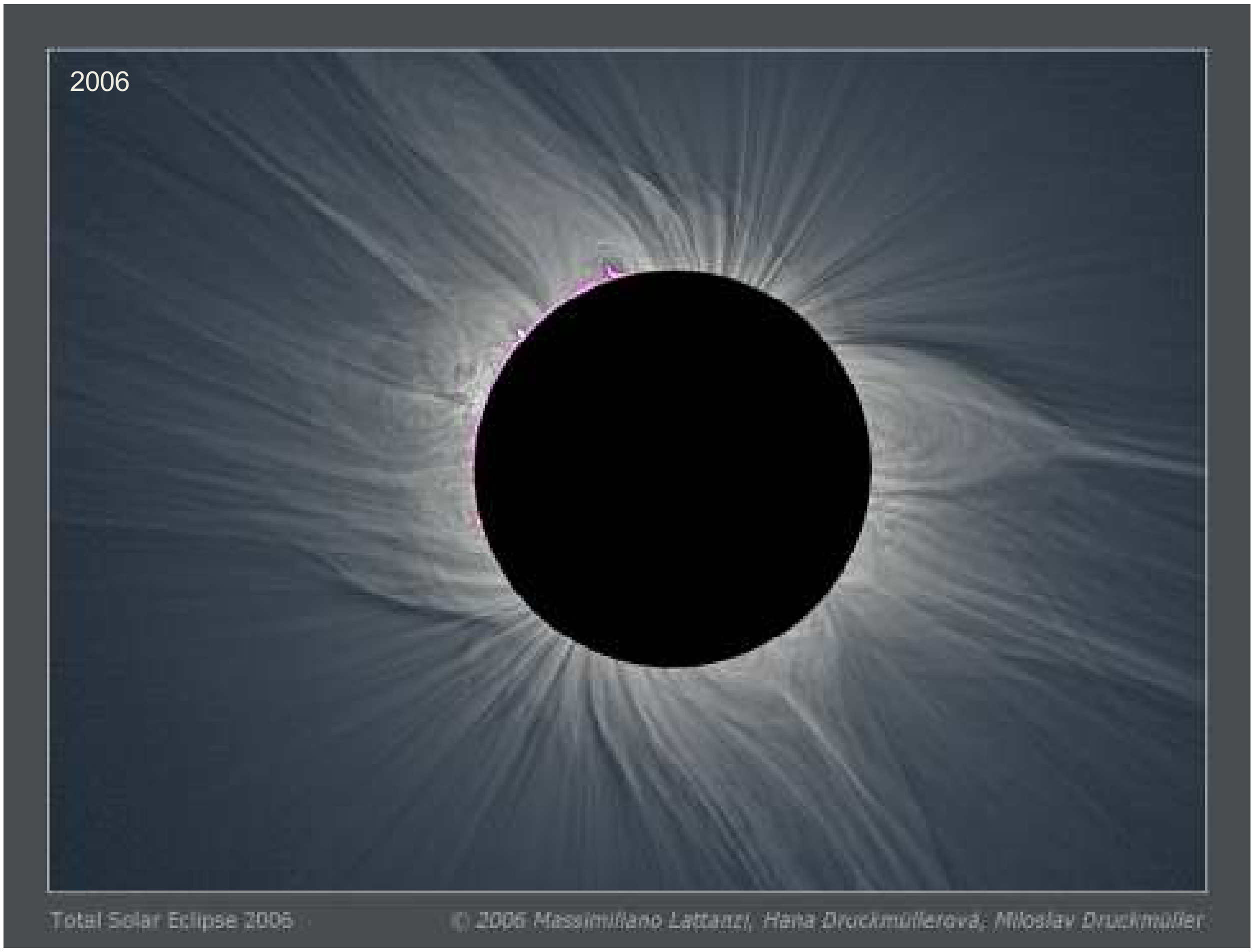
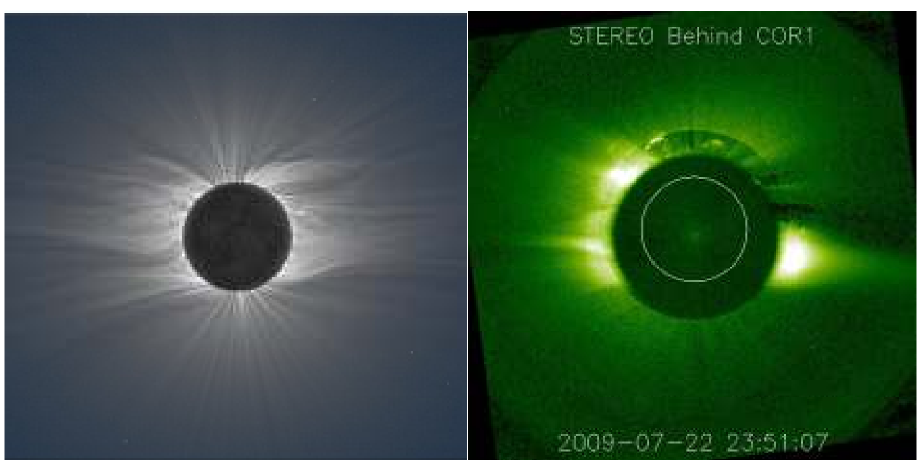


Figure 3. Eclipse image taken at the total solar eclipse in 2006.

Figure 4. A portion of the image taken during the total solar eclipse in 2008.



Eclipse 7-22-2009 COR1 7-22-2009

Figure 5. A comparison showing the highest resolution space-based coronagraph and an eclipse image both taken on the same day. It is clear that the fine-scale structure of the corona is not resolved even in the best current coronagraph images.

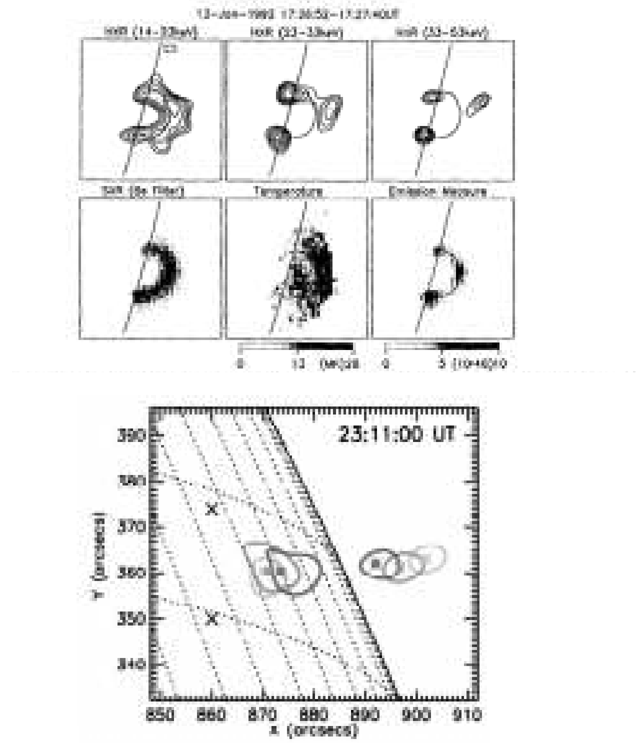


Figure 6. RHESSI observations show hot plasma sources present above flaring loops that are consistent with heating by reconnection jets. (from Sui and Holman)

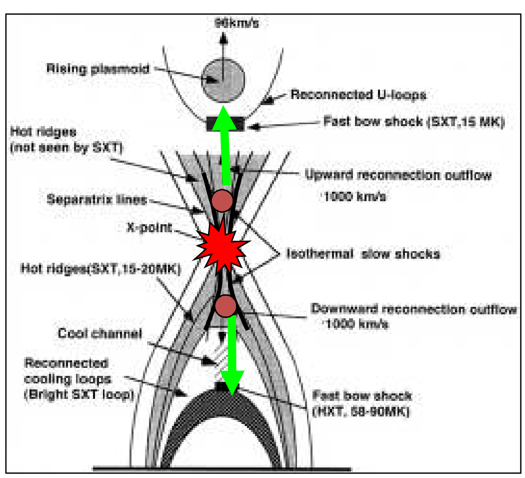


Figure 7. A schematic illustrating one model for reconnection in the high coronal resulting in flare

A Proposal for a Computational Heliophysics Innovation Program (CHIP)

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1. The changing high performance computing landscape. The last several years have seen dramatic developments in the field of high performance computing (HPC). Presently available computer clusters promise to provide heliophysics researchers with access to tens of thousands of CPU cores. For example, the Kraken machine at the University of Tennessee's National Institute for Computational Sciences (NICS) consists of 8,256 compute nodes, each of which contains two six-core AMD Opteron processors (for a total of 99,072 cores). The NCSA Blue Waters machine, scheduled for completion in 2011, will offer more than 300,000 compute cores (utilizing IBM's Power 7 chip) and is expected to achieve a peak performance in the 10 petaflops range. The next decade will likely see the emergence of even more powerful "megacore" machines – probably a combination of CPUs and Graphics Processing Units (GPUs) or other "CPU-acceleration" technologies – providing the computational equivalent of 1-10 million latest generation CPU cores. Indeed, the Nebulae CPU-GPU cluster at the National Supercomputing Center in Shenzhen, China already makes use of this new "heterogeneous computing" approach: it consists of 4640 Tesla C2050 GPUs, each of which has the potential for achieving the performance of ~100-200 (depending on the application) Intel Nehalem cores. As of August, 2010, Nebulae was ranked #2 in the Top 500 (second only to ORNL's Jaguar cluster), having achieved a performance of 1.271 PFlops/sec on the linpack benchmark (largely due to its use of GPUs).

What do these new HPC developments mean for the heliophysics community? As we perform simulations with increasingly sophisticated numerical algorithms on ever larger machines, the gap between *global* modeling, which is typically some version of magnetohydrodynamics (MHD) (perhaps with extensions such as the Hall effect), and *local* kinetic modeling, which usually entails Particle-In-Cell (PIC) simulations with rather artificial boundary conditions, is narrowing. Increasingly, our community is recognizing the importance of *multiscale* simulations in which important kinetic processes (e.g., collisionless magnetic reconnection) are driven by realistic large scale initial and boundary conditions. Such multiscale simulations, which promise to fundamentally transform many aspects of our picture of the Sun-Earth interaction, are now within the reach of those who are capable of taking advantage of the emerging new HPC methods and resources (Figures 1 and 2).

Herein lies the challenge facing the heliophysics community. Participating in these exciting new HPC developments will not be a simple matter of tweaking existing legacy

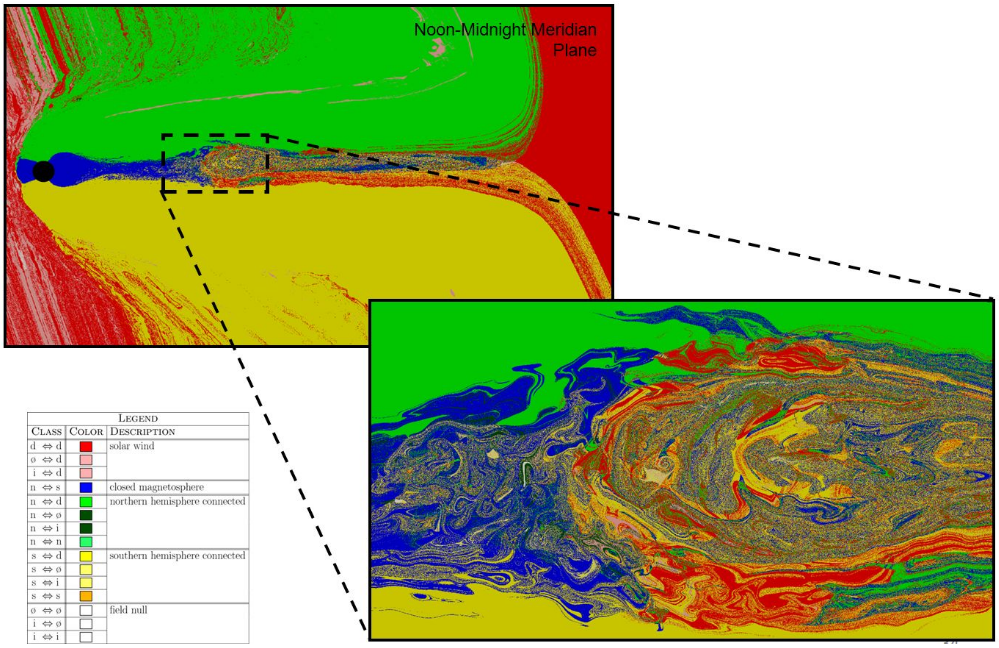

Figure 1 (courtesy of Homa Karimabadi). Global multiscale simulations are now within reach for those who are capable of fully exploiting the largest available machines. The image above shows a cut through the noon-midnight meridional plane of a magnetosphere simulated with the hybrid code H3D (in the hybrid model, ions are treated fully kinetically while the electrons are treated as a fluid). This simulation ran on 98,304 cores on the Kraken machine at the University of Tennessee's National Institute for Computational Sciences (NCIS). The colors in the image represent distinct three-dimensional magnetic field topologies (e.g., blue represents closed magnetic field lines, red represents solar wind field lines, and green/yellow represent open field lines). To our knowledge, this is the first simulation of a global magnetosphere to demonstrate the development of stochastic magnetic field regions in the magnetotail during turbulent reconnection.

codes (in the modern rapidly evolving HPC landscape, "legacy" may well mean "several years old") to run on new architectures and assuming the codes will gracefully scale up to larger machines. Often, an algorithm which scales well up to several thousand cores (typical for most state-of-the-art heliophysics applications such as global MHD) requires significant modification to scale up to 10,000-100,000 cores (implicit time stepping algorithms, for example, are notoriously difficult to scale up to very large numbers of processors). CPU-GPU programming presents new challenges, since porting existing codes to these heterogeneous architectures requires translation to one of the supported GPU languages (e.g., OpenCL or CUDA), and this essentially amounts to rewriting the code. Finally, after one scales a code up to 100,000 cores, old data analysis and visualization paradigms become irrelevant. For example, copying 100's of TB of PIC data over the network and analyzing the data with an application running on one's desktop is not feasible. New remote, parallel data visualization and mining techniques must be applied to such large datasets, and the heliophysics community must embrace this new approach to simulation data analysis if it is to flourish in the next decade.

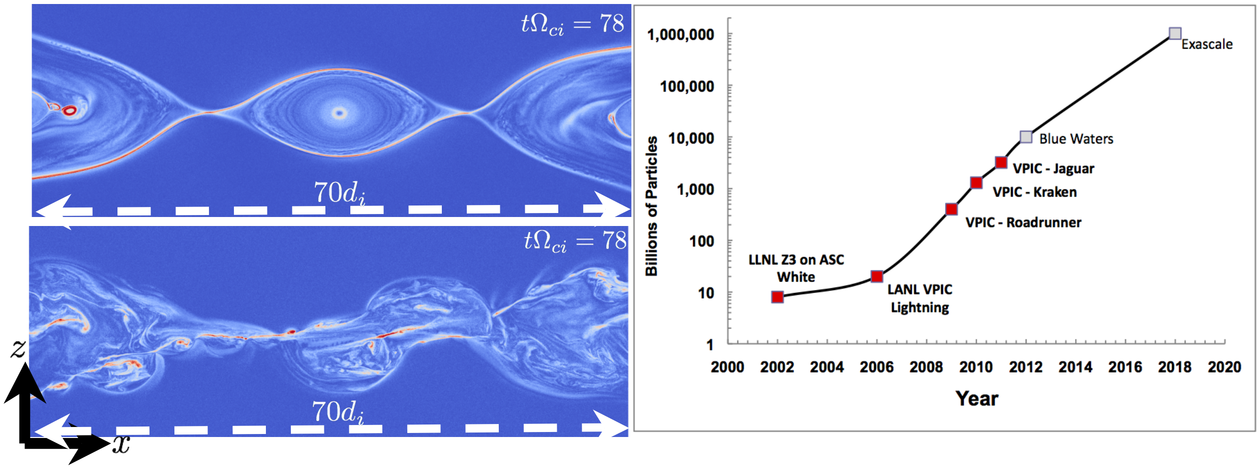

Figure 2 (courtesy of Bill Daughton). The last several years has seen an exponential explosion in the sizes of PIC simulations (right panel). Several years ago, simulations with 10 billion particles were possible; such simulations have made possible large ("large", by PIC standards, currently means ~100 ion inertial lengths) two-dimensional simulations with realistic proton/electron mass ratio. An example of such a simulation is shown in the top image of the left panel. Nevertheless, PIC simulations with a trillion particles are now possible on machines like Kraken, making large three-dimensional simulation (though not yet with realistic mass ratio) possible (bottom image of left panel). These new three-dimensional simulations – which show the development of microturbulence and complex electron scale current filamentation – have radically changed our understanding of the nature of three-dimensional magnetic reconnection.

2. The need for a NASA high performance computational heliophysics program. We summarize the challenges facing the modern computational heliophysics researcher as follows:

1. **Develop new multiscale/multiphysics algorithms – tailored to specific compelling heliophysics problems -- which have the potential to scale up to 100,000 compute cores and beyond.**

2. **Rapidly take advantage of emerging new hardware (e.g., GPUs and other CPU-acceleration technologies which are already appearing in supercomputers such as *Keeneland* in the U.S. and *Nebulae* in China).**

3. **Find innovative ways to mine, visualize and analyze the massive amounts of multi-dimensional, muli-variate data which will be produced by the next generation of multiscale simulation codes.**

While there are solutions to these challenges, progress will require a substantial investment in software development that is *agile* enough to respond to the rapidly evolving HPC landscape. Since the pace of technological innovation in HPC will only increase in the next decade, the pace of computational heliophysics innovation must also increase, or our field risks stagnating. We posit that the best way to maximize the

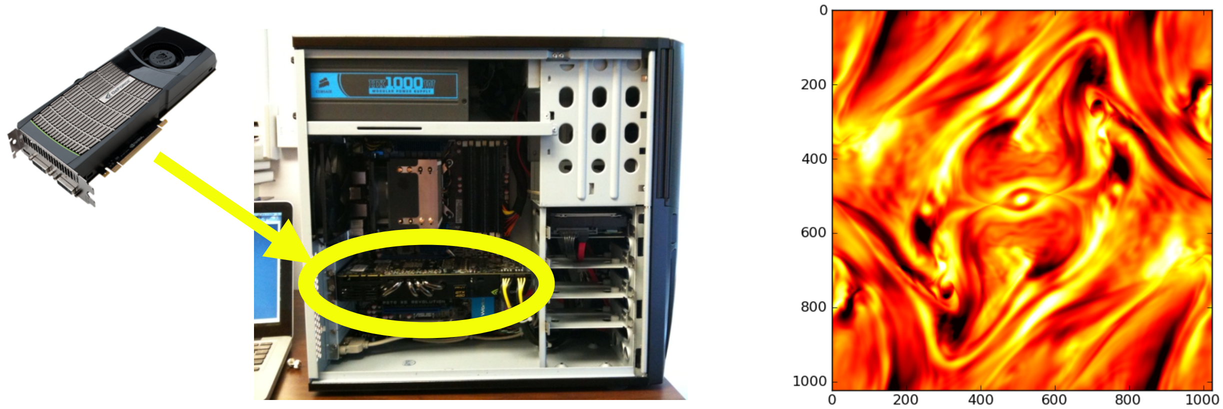

Figure 3 (courtesy of John Dorelli). New technologies such as Graphics Processing Units (GPUs) are bringing the power of moderately sized computer clusters (several hundred compute cores) to the desktop. The left panel show a desktop enabled with an NVIDIA GTX 480 GPU, which can now be purchased for under $3K. The right panel shows results of a Hall MHD simulation of the Orzag-Tang vortex on a 1024x1024 mesh, which ran on our GPU-enabled desktop 58 times faster (in double precision) than the sequential algorithm (an explicit MUSCL-Hancock scheme) on a single Nehalem (Intel i7) core. The image in the right panel shows the out-of-plane component of the magnetic field that develops (even in the absence of an initial out-of-plane field) due to the Hall effect.

productivity of heliophysics science in the coming decade -- in which the definition of "compelling science" may not only vary across the community but also evolve rapidly in response to advances in what is technologically possible – is to **distribute the investment across the entire computational heliophysics community.**

There are several arguments favoring a distributed, "grass roots" (rather than a more centralized) approach to NASA investment in computational heliophysics. First, we argue that concentrating resources – for example, by creating one or several "Centers for Computational Heliophysics" to support fewer "critical mass" groups over longer periods is not the way to promote rapid evolution of our field in response to rapid changes in the HPC environment. Such a center would not be as agile as a more distributed community effort in taking advantage of the new opportunities created by qualitative advances in HPC. For example, such a center might – due simply to the makeup of its members -- not have sufficient expertise and/or interest in pursuing particular projects (e.g., making Jacobian-Free-Newton-Krylov methods scale up to 100,000 cores, porting a code to a CPU-GPU cluster, etc.), despite the fact that such technologies might facilitate significant breakthroughs on problems of interest to a large fraction of the heliophysics community. While funding a few large centers over longer periods (say, 5 years) serves an important function by providing the stability necessary to train the next generation of computational heliophysicists, we strongly argue that funding such centers should *not* be done at the expense of funding smaller groups. On the contrary, we argue that funding a larger number of smaller, independent groups (who can explore many different approaches and methods), is the most efficient way to optimize the scientific return for investment in an HPC environment which will continue to rapidly evolve in the coming decade.

A second argument in favor of the distributed approach is that emerging new technologies are bringing the power of moderately sized computer clusters (containing several hundred compute cores) to the desktop for a small fraction (~1/10) of the cost. For example, one can purchase an NVIDIA GTX 480 GPU for under $400 and achieve (with a nontrivial but not prohibitive programming effort) the computational equivalent of 50-100 Intel Nehalem cores for under $3000 (Figure 3). Direct NASA support for smaller groups wishing to port their codes to such new architectures would help to bring the benefits of HPC to a larger fraction of the heliophysics community.

Another issue that argues for a more distributed approach is that it is becoming increasingly difficult for a single (or a few) "critical mass" group(s) to comprehensively keep track of rapid advances in HPC technology (which may take the form of new algorithms or new hardware). For example, only a small number of codes are currently running on the largest machines, adapting to new architectures such as GPUs, or taking advantage of new, sophisticated numerical algorithms; it is not clear that the rest of the heliophysics community (even that subset of the community focused on computation) fully appreciates the extent to which "state of the art" simulations of just several years ago have become obsolete (Figure 2). This state of affairs also highlights the important role that NASA can play – by providing financial incentives -- in making sure that the heliophysics community as a whole remains in tune with an exponentially expanding HPC frontier that is rapidly approaching the exascale.

3. Theory and modeling in the previous decadal survey. The theory, modeling and data analysis panel of the 2003 solar and space physics decadal survey focused on the notion of "coupling complexity," defining a "systems" approach to heliophysics in which multiple techniques (theory, computation, and data analysis) are brought together in a coordinated fashion to attack the problem of coupling different regions across multiple spatial and temporal scales. The panel recommended a large scale, concentrated approach in which NASA would create a new research program – the Coupling Complexity Research Initiative (CCRI) – that would do the following:

1. **Provide 5 years of funding at a level which would support "critical mass" groups composed of multiple graduate students, postdocs, research scientists and even new faculty or permanent staff.**

2. **Provide funding for the supported groups to purchase computer hardware.**

3. **Encourage and facilitate the delivery of "community models."**

The panel further recommended that about 10 such groups should be funded at a level of about $500,000 - $1,000,000 per year. The establishment of such an ambitious program by NASA would likely entail cuts in other parts of the Heliophysics Science Division's R&A budget (which in FY04 stood at roughly $63M/year and now stands at around the same number). The 2003 decadal panel thus recommended that the CCRI should be a cross-agency initiative led by NASA but involving other agencties (DoE, NOAA, and/or DoD).

For the reasons outlined in Section 2, however, we suggest that the CCRI, as proposed in 2003, should be reformulated so that it is more in tune with the modern, rapidly evolving HPC landscape. Gone are the days when a research group can push the computational envelope by purchasing a several hundred node Beowulf cluster and housing it in a dedicated computer lab (paying several grad students and postdocs to maintain the machine and the software which runs on it). The supercomputers used by future generations of space physicists performing cutting edge simulations will require their own dedicated state-of-the-art facilities with armies of computer scientists maintaining them (e.g., the NCSA Blue Waters machine), and a substantial software effort will be required to fully exploit these machines. The issue is not that a large fraction of the heliophysics community will not have access to such machines; the issue is that only a small fraction of the community has developed applications which are capable of scaling up to them! What is needed is a program which facilitates rapid *community-wide software innovation* in response to rapidly evolving HPC technologies.

We further suggest that the proposed CCRI's emphasis on a small number of "top down", centrally organized groups consisting of multiple students, postdocs and research scientists – all presumably revolving around a much smaller number of permanent staff or faculty – is not the most efficient model for rapid progress in multiscale heliophysics modeling. Indeed, much has been accomplished within NASA's current R&A framework (e.g., SR&T, the Heliophysics Theory Program, etc.) by the relatively small number of groups who have managed to position themselves to make full use of the largest machines. What is needed is a program to *increase the number of such groups*.

4. Supporting grass roots innovation in computational heliophysics. Motivated by the discussion in the previous three sections, we here propose that NASA should create a **Computational Heliophysics Innovation Program (CHIP)** to support grass roots innovation in high performance computational heliophysics. By "grass roots," we emphasize the inherent benefits of distributing the investment as broadly as possible over the computational heliophysics community, shifting the balance away from large centers and toward multiple, less permanent projects. The CHIP program would:

1. **Provide regular support for 1-3 year periods (we envision a multi-tiered approach in which shorter-lived and more risky investigations could be funded alongside longer term more vetted projects), at a level of around $100,000-$400,000 per year, for "agile" groups consisting of 2-3 graduate students, or 1-2 postdocs, directed by a single PI.**

2. **Require the supported groups to identify one (or several related) focused and compelling heliophysics problem(s) for which innovations in high performance computing (e.g., inventing/applying new algorithms, porting existing codes to new architectures, etc.) would facilitate transformational (non-incremental) progress on the identified problem(s)**

3. **Provide longer term support (5 years), at a level of $500,000-$1,000,000 per year, for 1-2 larger "centers" tasked with: a) facilitating community access to high performance computational heliophysics applications capable of scaling up to the largest available computer clusters, b) educating the next generation of computational heliophysicists, c) purchasing and maintaining computer clusters (making use of state-of-the-art hardware) and making them accessible to the entire heliophysics community through a proposal system.**

Examples of the types of activities smaller groups would be funded to engage in might be:

- Developing heliophysics codes which, due to the very large problem sizes necessary to make significant progress on a compelling problem, must scale to the largest available machines (currently ~100,000 compute cores).
- Developing smaller scale applications that run on more exotic or experimental architectures (e.g., GPUs) that are expected to make up a significant fraction of the future HPC landscape.
- Inventing new numerical methods that perform better on the latest HPC hardware on problems of interest to the heliophysics community.
- Developing new data mining, analysis and visualization techniques for very large datasets produced by high performance heliophysics codes.

Examples of the types of activities a larger center might engage in include:

- Maintaining existing high performance heliophysics applications (perhaps developed by one or more of the smaller groups housed at other institutions) for community access.
- Purchasing and maintaining a CPU-GPU cluster and providing access to the heliophysics community (e.g., via a proposal system), along with support for porting selected codes to the new machine.
- Organizing a high performance computational heliophysics school to educate students in the latest HPC techniques and hardware developments.

We emphasize that all of the activities described above should be motivated by focused science problems of broad interest to the heliophysics community and requiring substantial effort to develop software that can fully utilize the most powerful available hardware. Smaller groups would justify their existence by arguing that the science questions they are focusing on require innovation at the frontier of HPC (e.g., developing new algorithms or numerical methods which scale to the largest machines, exploring new architectures, etc.). Larger centers would justify their existence as a community service designed to facilitate access of the HPC frontier to the rest of the heliphysics community. We strongly believe that this "grass roots" innovation model, supplemented by longer term support for educational and community support activities, is the best way to ensure that the heliophysics community keeps up with the truly exciting HPC developments that will occur in the coming decade.

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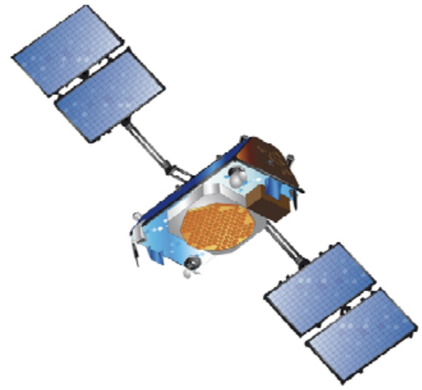
November 12, 2010

Flight Opportunities for Hosted Payloads on the Iridium NEXT Satellites

The purpose of this white paper is to ensure awareness of opportunities for flying sensors as hosted payloads on the commercial communications satellite constellation currently being developed by Iridium Satellite LLC, a subsidiary of Iridium Communications Inc. Referred to as Iridium NEXT, the system of 66 polar-orbiting low-Earth orbit (LEO) satellites is being plannedfor launch by Iridium beginning in 2015. Iridium Communications Inc. is a publicly-held provider of mobile satellite communications services.



Iridium NEXT Satellite

Launch campaigns are planned to begin in 2015, and the entire system is expected to be operational in 2017. Accommodations for hosted payloads have been incorporated into the design. Detailed interface specifications between the Iridium NEXT spacecraft and the hosted payloads are available.

The first generation of Iridium satellites facilitated numerous opportunities for observing the Earth, its atmosphere, oceans, ionosphere, magnetic field and other phenomena for scientists at academic, government, and military institutions. Studies have been sponsored by the Group on Earth Observations (GEO), an intergovernmental body based in Geneva, to validate the concept of hosting weather and climate related instruments on the Iridium NEXT platforms. The costs associated with hosting payloads on Iridium NEXT are expected to be significantly lower than developing dedicated space missions and the infrastructure required to operate them. This white paper invites consideration of other ideas by the solar and heliophysics scientific communities, and by the space weather operational community.

Schedule Urgency

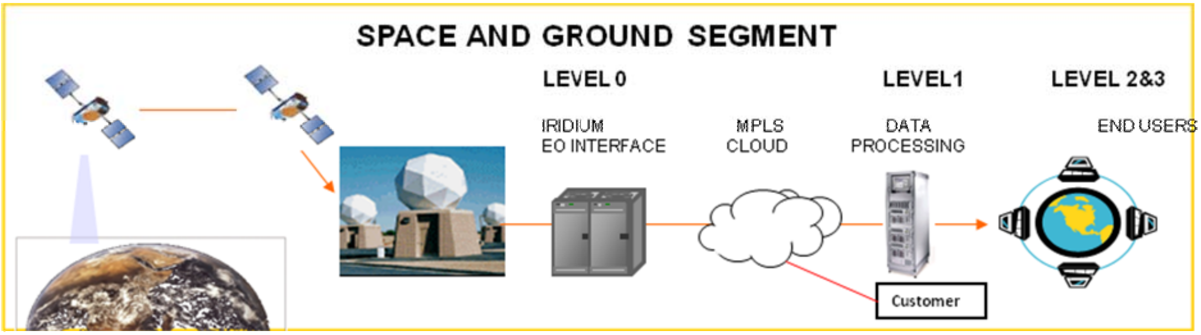
The engineering and business processes supporting the development of Iridium NEXT are mature and the system is moving into full development following the selection of Thales Alenia Space France as the prime contractor. Potential users of the hosted payload opportunities should initiate discussions with Iridium as soon as possible. This will enable compatibility studies during 2011 and 2012 to ensure that the final satellite design can accommodate any unique hosting requirements. Hosted payload slots must be reserved through a contract with Iridium. Delivery of the payloads for integration would be expected during 2013-2014. The first launch is planned for 2015, with completion of the constellation deployment in 2017.

The Iridium NEXT Constellation

When fully deployed and operational, the Iridium NEXT system will contain 66 satellites, 11 in each of 6 orbital planes, 6 in-orbit spares. The circular polar orbits with inclinations of 86.4 degrees provide continuous coverage of 100% of the Earth's surface. The 780 km altitude has an orbital period of roughly100 minutes for each satellite. Iridium has contracted with Space

Exploration Technologies Corp., or SpaceX, to be the primary launch services provider for Iridium NEXT using Falcon 9 launch vehicles.

Individual satellites are expected to have a design life of 10 years. Six in-orbit spares and additional ground spares will help ensure continuity of service in the event of malfunctions.



Each Iridium NEXT satellite will have four cross-links to communicate directly with neighboring satellites, two in its own orbit plane and two in adjacent planes.

The Iridium operations infrastructure is expected to provide real-time user command and control to the hosted payloads and real-time relay of data to and from the hosted payload in space.

The satellites will fly with one side always facing nadir (pointing at the Earth) and one side facing in the direction of the velocity vector. This pointing is stable to within a 0.45 degrees half cone angle.

Accommodations for Hosted Payloads

The Iridium NEXT satellites have been designed to accommodate a "standard" payload that meets the specifications shown in the table. These should be considered approximate and subject to change. Detailed interface requirements are available on request from Iridium.

There is one hosted payload location available on each satellite. However, multiple instruments may be located within its volume if desired. They must share a common electrical interface to the spacecraft and must conform, in aggregate, to the interface requirements.

Iridium NEXT Hosted Payload Specifications	
Weight	50 kg
Payload Dimensions	30 x 40 x 70 cm
Payload Power	50 W average (200 W peak)
Payload Data Rate	<1 Mbps, Orbit average ~100Kbps

Iridium NEXT Hosted Payload Specifications

Users may contract for slots on multiple satellites if the scientific or operational objectives require or would benefit from more than one sensor.

The volume allocated for the hosted payload is on the nadir-facing surface at the leading end of the spacecraft.

This location is expected to provide unobstructed viewing directions towards nadir and Earth limb.

Very limited moving parts will be allowed and only after careful accommodation study. Such a subsystem, e.g., scan mirrors, may not impart disturbances or torques to the spacecraft that would interfere with its primary mission.

A spacewire interface is used between the payload and the spacecraft data management system.

Ball Aerospace & Technologies Corp. (Ball Aerospace) has collaborated with Iridium for accommodation studies of space weather payloads in the past. This relationship can be leveraged to meet specific customer needs regarding heliophysics hosted payloads. Ball Aerospace would be interested in systems engineering services for the interface between the heliophysics community and the Iridium NEXT constellation.

Examples of Remote Sensing Using Iridium's Current Network

Applications include communications with, and data relay from, large networks of widely dispersed terrestrial instruments, remote sensing and *in-situ* measurements by instruments onboard the Iridium satellites. Examples include:

- Argo profiling floats for global measurement of sea surface temperature, salinity, and currents
- Tsunami early warning networks
- Meteorological data buoys
- Iceberg tracking
- Fisheries monitoring
- Atmospheric profiling
- Magnetometers for Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE)
- Real-time *in-situ* space weather data

These projects have benefited from Iridium's cost-effective global coverage with continuous real-time command and data availability.

Iridium and an international team of independent scientists, weather experts and industrial partners have conducted technical studies for the GEO and for U.S. space and weather agencies. These studies have validated at a high level the technical feasibility and estimated costs of placing certain mission-specific sensors on Iridium NEXT satellites. For example, Iridium has studied at a high level:

- GPS Radio Occultation (GPSRO) to measure lower atmospheric profiles such as temperature, pressure, and humidity
- GPSRO to measure electron density profiles in the ionosphere
- Broad-band radiometers for monitoring the Earth Radiation Budget
- High precision measurements of Total Solar Irradiance
- Measurements of other atmospheric constituents (e.g., ozone profiles)
- Radar altimetry for sea surface topography, including waves and ice
- Multi-spectral imagers for ocean color and land imaging
- Instruments for space weather monitoring and forecasting

Schedule Details, Key Milestones – These are planned dates and subject to change.

Date	Milestone
2010	Start of full scale development. Feasibility studies and acceptance of slot commitments for hosted payloads.
Q1 2012	Continuation of feasibility and risk-reduction studies. Acceptance of slot commitments to ensure deployment with first launch.
Q1 2013	System Critical Design Review. Hosted Payload Interface Specification finalized. Slot commitment window closed.
Q1 2014	Initial hosted payload delivery to Iridium. Integration and qualification.
Q1 2015	First Iridium NEXT launch. Deployment of Iridium NEXT with hosted payloads into orbit. Hosted payload turn on, check out and initial operations.
Q2 2017	Launch campaign complete.
Q3 2017	Iridium NEXT system operations begin. Full operation of all hosted payloads.

Business Models, Costs

The capital and operational costs of placing payloads on Iridium NEXT satellites are in many cases expected to be significantly less than the cost of developing and deploying dedicated satellites and the necessary infrastructure to support them. A study by Futron Corporation has demonstrated this by comparing annualized costs for various sensor missions flown in the past and comparing them to what they might cost on Iridium NEXT. On average, these costs are less than 25% of those of a dedicated mission. The price of deploying a “standard” hosted payload into space on Iridium NEXT consists primarily of a hosting fee paid to Iridium and the cost of the sensors themselves. There is also a modest, non-recurring engineering cost and annual data delivery charges once the data delivery starts. The hosting fee for a single hosted payload slot on Iridium NEXT is expected to be less than $9 million. The total price can be further reduced through volume discounts if the mission calls for a large number of hosted payloads across the constellation.

Summary of Benefits of Iridium NEXT

- Unprecedented geospatial and temporal coverage – 66 interconnected satellites with coverage over entire globe
- Real-time, low latency relay of data to and from payloads in space
- Communications backbone provided by the Iridium system itself
- User control – Data delivery and access to hosted payload, seamlessly through Iridium infrastructure or private gateways
- Cost effective – Access to space at a fraction of the cost of a dedicated mission
- Exclusive – No other opportunity like this is likely to become available in the coming decades

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The Need for Consistent Funding of Facilities Required for NASA Missions

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There are certain government facilities that are vital to the success of many NASA Heliophysics missions, but are only partially, or not at all funded by NASA. These are facilities that are too large, complicated, and/or long-lived to be funded by individual programs or missions. They are primarily used for the calibration and test of space instrumentation, yet their continued existence is precariously dependent on funding decisions not always in the best interests of NASA.

One example of such a facility is Beamline-2 (BL-2) at the Synchrotron Ultraviolet Radiation Facility (SURF) at the National Institute of Standards and Technology (NIST) in Gaithersburg, Md. NIST operates SURF BL-2 as the primary standard for EUV calibrations in North America. It is the only beamline which provides direct viewing of the continuum source from the synchrotron, thus providing the highest level of accuracy for the calibration of EUV instruments for solar and planetary atmosphere missions. Other synchrotron beamlines at SURF and at other facilities worldwide provide only secondary calibration capability. Using these other facilities for calibration of EUV instruments causes the measurement uncertainties to increase significantly. In other words, there is a science impact to NASA if SURF BL-2 were to be no longer available.

While the synchrotron itself at SURF is supported by NIST, currently the funding for maintaining BL-2 is split between NASA Earth Sciences, NASA Heliophysics, and the NOAA GOES Program. This split has developed historically, is rather tenuous, and is constantly being renegotiated. In these tight budget times, Earth Sciences and GOES have committed their funding with the understanding that each of the other groups will contribute, but if Heliophysics pulls out, that may result in the closure of BL-2. There is a concern that any decrease, no matter how temporary, in the funding of BL-2 will result in the permanent closure of that beamline to NASA programs and the re-purposing of the beamline to other NIST uses. BL-2 is a facility that must be maintained continuously or it goes away. Decreases in funding for even a year could cause NIST to close the beamline permanently.

It has been suggested that the funding of a facility like BL-2 be done on a project-by-project basis, but this would be too uncertain and inconsistent to be workable. Note that the NASA SDO-EVE program requires the use of SURF BL-2 for the lifetime of the SDO mission, which is until 2015 for the nominal mission and longer for an extended mission. Supporting BL-2 is not currently in the SDO-EVE or in other project budgets. The cost to support BL-2 via a project would be the same to NASA. The cost for EVE and other projects to go to different calibration facilities would be even greater, since they have higher charges for calibration time, and because new support equipment would have to be built. The funding of a facility resource like SURF BL-2 needs be put in someone's budget on a more permanent and continuous basis and at a higher level than Earth Science, Heliophysics, and the various NASA projects that use the facility.

SURF BL-2 is an explicit example, but there are other facilities that should be put under an umbrella of support for similar reasons. For instance, NASA GSFC has a electron source that is used for the calibration of energetic electron detectors. It is aging and only continues to exist only because of the will of the researchers who maintain it, yet is a valuable resource for NASA.   There are other radiation sources used for testing and calibration of NASA instruments that are scattered about the country, many at universities, but not all are under any level NASA control or funding, so could cease to be useable by NASA projects at any time.

There is also no clear avenue for the creation of new facilities to support NASA missions. An example of this is the need for new standard reference sources. There is currently a wavelength gap between hard X-rays and the EUV, where current facilities are incapable of providing accurate calibrations of detectors and secondary sources. This is a wavelength region of interest to Heliospheric science, but the creation of a new facility is beyond the scope of the individual research programs who would use it.

In summary, NASA needs to develop a logical and stable way for the creation and maintenance of the calibration and test facilities, such as SURF BL-2, required for the successful support of its own research and missions.

ALTERNATE MAGNETIC THERMODYNAMICS

Alternate Magnetic Thermodynamics or Permadynamics in short for Permanent Magnetic Thermodynamics is the Attraction of Persistent Contact without Intervening Forces to its Real Value. It is Powerless to the Equalization of Heat to Forces but Transitive to its Intransitive Senses meaning, its Prefiguration Levels have both Balanced and Unbalanced potential due to its Genetic Drift which pretains to the Entropy's Finite Volume. Free Motion is an Alternate, Recuperative and Regenerative Process of Permadynamics Life Cycle.

To a indefinite extent the scale of value towards the extent of Space and Solar Physics are incomparable for any reasonable consideration. The Intransitive and Transitive manner of its Construction Sense's is a Direct Intuitive understanding between its Volition of Persistent Contact and its Law of Averages. Magnetic Energy is randomly converted inside a Vortex capable of filling a Energy Mass with the objective to Understand its Prefiguration Levels usual Standard

We should have the Unrestrained Pleasure as part of its and our very own omission of force performed without a break to be held in consonance with the Orbit Motion of this Magnetism as it seperates from its Balance of Energy to Affinity. NASA and the Woirld already understand the Benefits of Quantum Electrodynamics. Permadynamics without Resurgent Composition is our Disroportionate Renewable Energy that is and will alway's be the Strategy of Space Exploration.

Thanks

Jesse R. Frazier jr.

Value of Enhanced Mentoring in Space and Helio Physics

Nicholas Gross, Center for Integrated Space Weather Modeling, Boston University

The Center for Integrated Space Weather Modeling (CISM) is a Science and Technology Center funded by the NSF to develop the next generation of space weather models that can be used in both research and operations. CISM also has an education mandate to support the training of the next generation of space physicists. As part of that effort, students working on CISM related projects are encouraged to interact with each other and CISM researchers through a variety of CISM related activities. Exit interviews with CISM students who have graduated with Ph.D.'s have highlighted the perceived value of these activities. These activities allow for students to see science as a collaborative activity, provided a variety of role models, particularly for students from underrepresented groups, and allow students to ask questions about a broad range of academic activities not directly related to the science that they are doing. The value that students see in these activities can be thought of as enhancing the mentoring graduate students naturally get from their thesis advisor. The goal of this white paper is to highlight what we have discovered about the role of center wide mentoring based on what was uncovered from the exit interviews.

Based on exit interviews, the CISM sponsored activity that students most often identified as valuable was the yearly 'graduate retreat' held just prior to the annual CISM All-Hands meeting. A core group of CISM students organize and attend this meeting each year. The only senior researchers at the meeting are the center director and an invited speaker. Prior to each meeting, students choose a general topic not directly related to research and invite a special guest who can speak to the topic. Past topics have included: publishing journal articles, writing a desertion, grant funding, finding a first position after graduate school, and balancing work and family life. In this way students are provided mentoring beyond science research that encompasses the entire academic life style. In exit interviews, students said that this activity provided significant guidance about their future in the space physics field specifically, and in the research environment in general.

In exit interviews, students provided specific value for attending the retreats. Students noted the value in getting to know other students working on similar problems and students who are working on different but related problems. For example, a student working on a magnetosphere problem could talk to a student working on a solar wind or ionosphere problem which might be connected. These connections from the retreat then continued through online interactions and get togethers at more formal professional meetings such a GEM, SHINE and AGU. Students also mentioned that the special topics covered were particularly valuable since they are not usually covered in any formal or organized way anywhere else. One student specifically was able to decide that an academic career was not to their liking because of the uncertainty involved in employment and funding. That student said that the group discussion followed by individual conversations with the guest speaker and the center director provided insight into that aspect of academic life. That student could then judge the amount of uncertainty involved and what they could be comfortable with. Several students commented about the relaxed tone of the retreat. Seeing a senior research, particularly the center director, in an informal setting put them at ease (he was ‘less scary’ as one student put it) and allowed the students to more freely ask questions and discuss the topics informally. Students also commented on the insight they gained about publishing papers, the grant funding process, and applying for a first position.

In addition to the retreats, students commented on the overall value of being a part of the center and engaging with a wide variety of researchers. During exit interviews, most of the students reported engaging with both students and senior researchers outside of their home institution. They saw significant value in that, with research collaborations, networking opportunities, and in finding role models. One female student commented that, though her thesis advisor was male, and she had a good relationship with him, she liked seeing and speaking with women who were in leadership roles in the Center. It was important to her to see women who were senior researchers and respected in their field, and who also had families and could speak to that experience. Thus by exposing students to the broader research community outside their home institution, they are more likely to find a suitable role model, even if it is one that they will not interact with on a day to day basis.

The graduate retreats were held just prior to, and in the same location as the CISM all-hands meetings, and students were encouraged to attend that meeting also. Students commented on the value of that meeting as well. In addition to more networking opportunities, seeing how CISM research priorities were set and getting a sense of where the research fit into the big picture was important to the students. One student commented that the all-hands meeting was different from other professional meetings. At most professional meetings science was presented as a finished product that was carefully laid out. The all-hands meeting showed how science, especially a in a big project, was done.

For the students involved in CISM, the added value of being part of a center included this ‘enhanced mentoring’ provided by engaging with the wide variety of researchers available in the center. The center funding will come to and end in 2012 and many of these activities will not be available. It is clear though that students would benefit from this advanced mentoring either as a stand alone program, or as part of a larger effort. I encourage the SSB to include a call in the decadal survey for support, partially in funding but mostly in leadership and vision, for other opportunities for enhanced mentoring for a broad range of students who are potentially interested in space and helio physics.

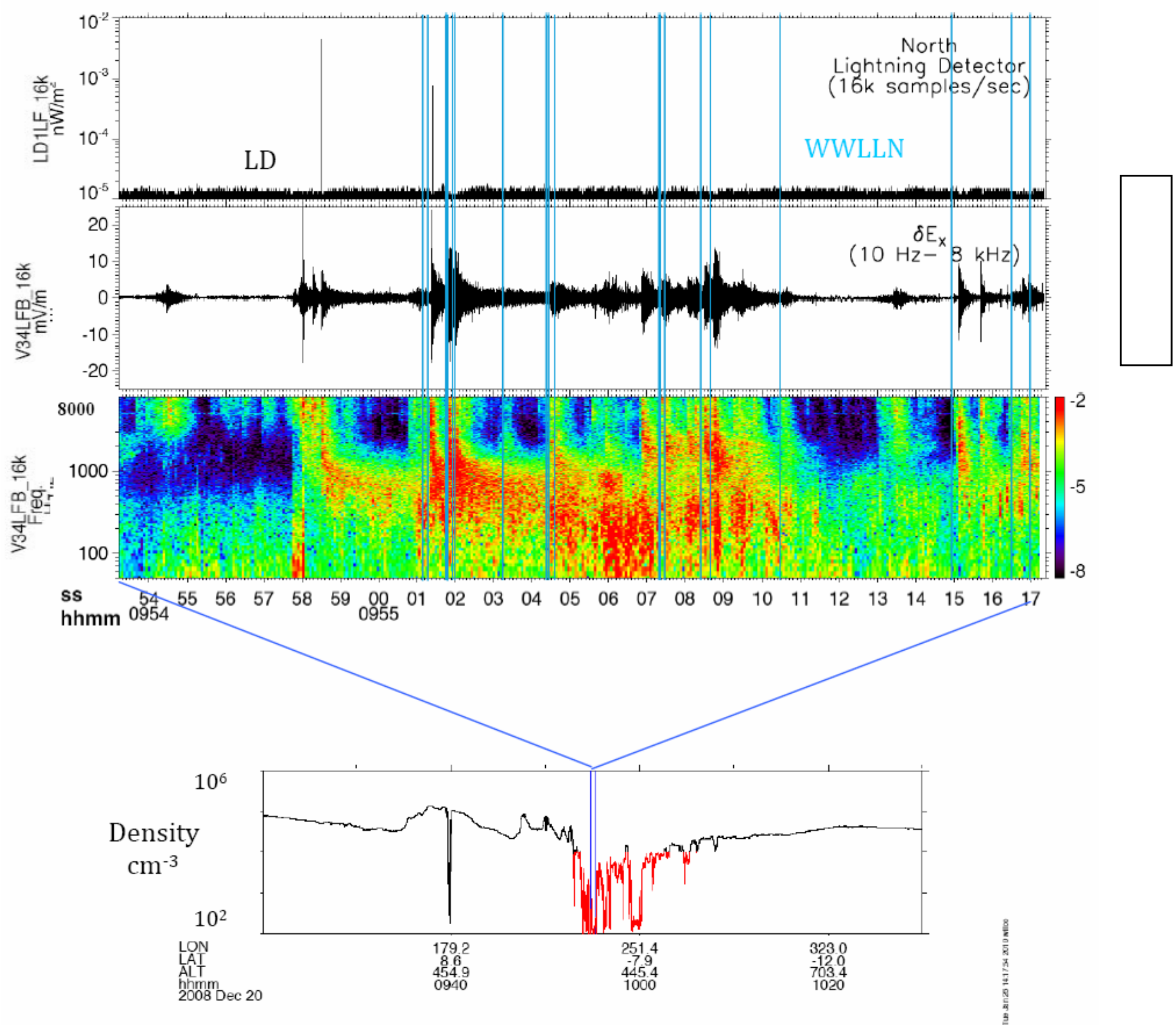
Lightning Influence on Ionosphere and Magnetosphere Plasma

Lightning Whistler Wave Characteristics. Lightning is one of the most powerful natural phenomena, with energy release rates of which can be over 10^{11} Watts . We have known about ionospheric and magnetospheric VLF (Very Low Frequency) plasma whistler waves since the 1950s and 1960s (see Helliwell, 1965), and even about lightning-generated ion whistler waves since the early years of the space program (see Gurnett et al, 1965). The well developed theory of the coupling of electromagnetic waves from lightning into whistler mode electromagnetic plasma waves, and the subsequent propagation in the ionosphere and magnetosphere has allowed the use of whistlers to study magnetospheric dynamics. For instance, one can use whistler duct motion to estimate magnetospheric electric fields (Helliwell, 1965). For these studies, it was shown that the whistlers propagated in plasma ducts within the magnetosphere and then coupled back into an electromagnetic wave to reach the ground based receiver. It was assumed that this required some wave amplification process for significant magnetospheric propagation, so the lightning whistler waves were consider like 'test' waves which were amplified in the unstable plasma at the expense of free energy in the particle distributions (through strong coupling to the trapped electron populations, for instance.). These ducted whistler waves were relatively rarely detected (compared to the number of lightning strokes), and therefore our main knowledge of these waves required both a duct and magnetospheric amplification, in order for the waves to be detected on the ground, or to cause particle pitch angle scattering resulting in precipitation such as 'Trimpi' events (Carpenter et al, 1984).

High Amplitude Lightning Waves Detected. The first vector electric field experiment on ionospheric rockets, flown directly over thunderstorms, was reported in 1985 (Kelley et al, 1985) where it was reported that the measured, lightning-generated whistler mode waves were much larger in amplitude than predicted (e.g. Park and Dejnakarintra, 1973). Since then several rocket flights have been conducted over thunderstorms to study the upward coupling of lightning generated emissions into the ionosphere. Li (1993) showed that over 85% of lightning events within 1,500 km of a rocket subtract resulted in upward going whistler waves detected at the rocket. Helliwell (1965) had already shown that these waves, once coupled into a whistler mode plasma wave, would refract into the vertical because of the strongly horizontally stratified ionospheric electron density. Indeed, the whistler waveforms detected by Kelley et al (1985) and all subsequent such experiments, generally showed that the whistlers were very coherent, having only a single monofrequency at each moment of time, thus indicating that there had been only one path to the rocket - namely vertically straight up. So, the picture emerged that every lightning event generates strong electromagnetic wave in the earth-ionosphere waveguide which couples into whistler mode waves over large areas (at least 2500 km, see Holzworth et al, 1999.) Indeed, the low frequency part of these waves (between, say, 500 Hz and 2 kHz, say) can propagate right out to the magnetopause (Holzworth et al, 1999). The vast majority of these waves are found to be propagating as oblique whistlers, and are not necessarily captured in any magnetospheric plasma duct. Note that once inside the magnetosphere, these whistler mode waves do not easily couple back down to the ground, but rather can bounce around between the ionosphere and the magnetopause and become completely phase mixed as they combine with other such lightning generated VLF waves.

Recent Advancements. Results from the Demeter (cf. Berthelier et al, 2008) and C/NOFS (Holzworth et al, 2010) are providing new evidence for the importance of lightning to ionosphere and magnetosphere plasma processes. We have known since 1982 (Woodman and Kudeki, 1982) that lightning can trigger explosive ionospheric plasma density perturbations called Spread-F (where the ionospheric radar returns echos from multiple layers simultaneously with the same frequency.) Indeed the study of these ionospheric irregularities is a major reason for the C/NOFS satellite (De la Beaujardiere et al, 2004).

Now the importance of lightning to the irregularities is becoming stronger with results showing that lightning can be the largest electric



Electric field, optical lightning and density measurements on C/NOFS at 450 km Altitude. Blue lines are WWLLN lightning times. Electron density was < 100/cc in the event.

Field signal in deep density cavities associated with spread-F. This implies that lightning may be a more important stimulator of ionospheric irregularities than previously anticipated. Such perturbations are thought to be a primary driver for radio scintillation which affects radio communication and GPS signals as they pass through the ionosphere.

Suggestion for Future Work. Lightning has been shown to be much more important to ionospheric and magnetospheric phenomena than previously considered. Lightning is very powerful, happens all the time (40 to 80 strokes per second globally), penetrates the ionosphere with every stroke, and propagates as plasma wave energy all the way to the magnetopause. Yet traditionally, space scientists have not considered lightning to be energetically important to ionospheric and magnetospheric dynamics.

Consider that some of the strongest plasma waves in the magnetosphere are so called hiss waves (banded whistler mode emissions around a few kHz.) The plasmaspheric hiss is likely strongly linked to phase mixed, and multiple reflected lightning-generated whistler waves. Yet, we do not know what is the energy input into the magnetosphere from lightning. These waves may be the dominant source of pitch angle scattering and subsequent precipitation of energetic, trapped particles in the magnetosphere: i.e. a major loss mechanism for the radiation belts. These strong plasma waves may be important in other wave particle interactions such as reconnection at the magnetopause, or triggering of stimulated emissions in the magnetosphere and ionosphere.

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SWIRES, a Solar Wind Instrument for REmote Sensing

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ABSTRACT

SWIRES (**Solar Wind Instrument for REmote Sensing**) is a visible-light imager that provides solar wind bulk density measurements from an 840 km Sun-synchronous terminator polar orbit. The imager will provide a continuous view of sunlight scattered from heliospheric electrons. When the much larger background contribution of visible light from zodiacal dust and the sidereal sky is subtracted, the residue can be analyzed in terms of the heliosphere's fundamental plasma parameter, density. Analysis of these data will allow reconstruction and interpretation in 3D (three dimensions) using state-of-the-art modeling techniques. The imager views within the sky hemisphere towards the Sun, covering elongations $5° < \varepsilon < 65°$. A thorough analysis will provide global heliospheric 3D densities. The analyses from this instrument will answer many fundamental science questions specific to previous NASA surveys that describe the aim to understand the Sun, heliosphere, and planetary environments as a single connected system.

I. INTRODUCTION

The SWIRES (**Solar Wind Instrument for REmote Sensing**) mission is directed toward answering the primary science objectives from NASA's *"Sun-Earth Connection 2003 Roadmap to Understand the Sun, Heliosphere, and Planetary Environments as a Single Connected System"* and NASA's decadal survey challenges in *"The Sun to the Earth and Beyond:"*

1) Understand the changing flow of energy, matter and magnetic field from the Sun and throughout the heliosphere and planetary environments.

2) Explore the fundamental physical processes of solar and space plasma systems, and their interaction with solar system bodies.

3) Define the origins and societal impacts of variability in the Sun-Earth connection.

Specifically, SWIRES will:

- Explore changes in heliospheric material and flow [NASA Objectives 1 & 2]
- Understand the relationship between CMEs and the Sun's corotating structures [NASA Objectives 1 & 2]

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- Investigate how transient phenomena affect Earth & other planetary bodies [NASA Objectives 1, 2 & 3]
- Understand plasma transport and solar wind physics [NASA Objectives 1 & 2]
- Measure processes that pertain to the societal impacts of solar events and allow their forecast at Earth [NASA Objective 3]

II. SCIENTIFIC GOALS AND OBJECTIVES

SWIRES data consists of remote-view, white-light images of the heliosphere. The white-light observations of the plasma heliosphere derive from Thomson-scattered light from free electrons in the solar wind. This is a minor but changing component (on the order of an hour to days) of total signal. Figure 1 shows a variety of these signals modeled and derived from Earth orbit (Jackson et al., 2010c). The images consist of photometric readings from the instrument's cameras with high-energy particle hits removed and with images rebinned onboard for telemetry to Earth.

Lessons learned from both the Solar Mass Ejection Imager (SMEI) (Eyles et al., 2003; Jackson et al, 2004) and the Solar TErrestrial RElations Observatory (STEREO) Heliospheric imagers (HI) (Eyles et al., 2009) indicate that a small, baffled white-light camera in relatively low Earth orbit with only modest spatial resolution of a fraction of a degree can achieve photometric imaging of the entire heliosphere. This will allow mapping of heliospheric structure from the Sun outward to beyond Earth's orbit with sufficient spatial resolution to measure heliospheric structure, but even more importantly will provide input to 3D models from near Earth in order to map the plasma content of the entire global heliosphere. Although 2D image data is being collected, **the ultimate goal is to provide 3D-reconstructed volumes of the whole heliosphere** through modeling for the purpose of studying the dynamics of space plasma systems. To this end, the University of California, San Diego (UCSD) heliospheric group has developed a 3D reconstruction code (Hick and Jackson, 2004; Jackson et al., 1998, 2008b) that inverts a 2D view to provide densities to the brightness observed. It does this at a lower boundary, and iterates to provide the best possible 3D reconstruction of the observations in density. This boundary can be used wherever it is available to extrapolate to the edge of the heliosphere and beyond.

SWIRES is a modest spaceborne instrument that, like SMEI, can revolutionize heliospheric imaging science. The fundamental purpose of the instrument is to view changing heliospheric brightness. Properly conceived, such an instrument enables a long term base to be removed from heliospheric images such that they map variable heliospheric structure from scales of a few minutes to several weeks. SMEI shows that this is possible, and that this allows imaging and 3D measurement not only of fast moving CMEs and their shock responses (Jackson et al., 2010a; 2010e), but also corotating regions (Jackson et al., 2010c). These analyses show the interactions between CMEs and these often more slowly-moving segmented dense solar wind features.

With an absolute calibration of 4% from bright stars viewed by the instrument, SWIRES will allow measurement of large heliospheric structures that rival the

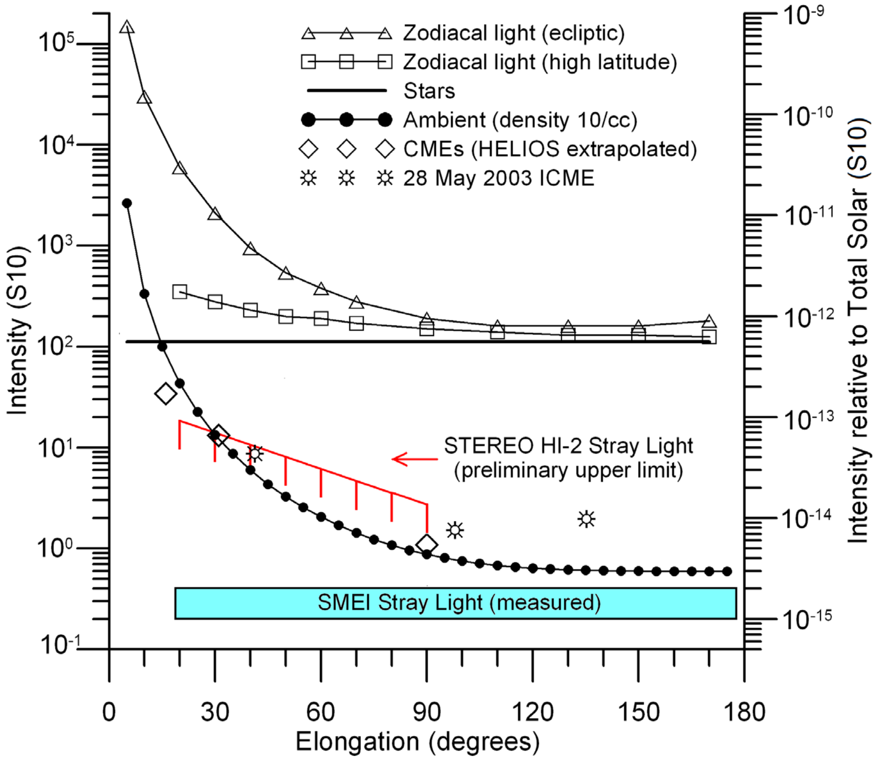

Figure 1. Surface brightness versus solar elongation for zodiacal and star light (from Allen's Astrophysical Quantities, Cox, 2000), and of expected CME brightness from observations using the Helios photometers and SMEI. Also shown is a calculation of an ambient heliospheric medium having a density of 10 cm^{-3} at 1 AU and an inverse-square density drop off with solar distance that matches the bright CME response. The SMEI stray light value is from Buffington et al. (2005), the STEREO HI-2 upper limit is from Eyles *et al*. (2009).

measurements of these same large structures in total density content from in-situ spaceborne measurements (Jackson et al., 2008a; 2010a,e). These structures are most finely resolved in 3D near the Earth where the number densities of lines of sight maximize (Jackson et al, 2008b; Bisi et al., 2009), and the 3D reconstruction can be most finely resolved. Here the measurements are well-resolved enough to indicate the shape and orientation of the structure fronts that can be timed from individual spacecraft at L_1.

The outward-flowing solar wind evolves from near the Sun to farther out, and the line of sight distance to each fine heliospheric feature seen at one solar angular distance can be expected to change. This means that the structure observed nearest the Thomson sphere (Vourlidas and Howard, 2006) dominates in any one image, and thus fine heliospheric features viewed in one image become indistinguishable from other fine structure as these features move farther away from the Sun on successive images. Thus, one can only measure an ensemble of structure as the heliospheric material moves outward gaining its location in a statistical sense. This works perhaps to locate the approximate boundaries of a CME, or the general location of a shock front, but works poorly to track small heliospheric structure details from the Sun to spacecraft that are as fine as can be measured by in-situ analyses.

From Earth, heliospheric structure characterization is available from other instrumentation, namely interplanetary scintillation (IPS) observations available from a number of ground-based observatories (Jackson et al., 2010), and is proposed from several other ground-based instruments such as the Murchison Widefield Array (MWA) now under construction in Western Australia or the LOw Frequency Array (LOFAR) now under construction in Western Europe. These analyses can be expected to gain considerable insight into heliospheric fine structure from the differences measured between bulk density available from SWIRES, and IPS observations that are derived from the small-scale (~150 km) density inhomogeneties in the interplanetary medium.

In addition, MWA and LOFAR have as a major proposed output, measurements of polarization from either the low frequency radio background or individual polarized radio sources. Faraday Rotation observations are the integral component of a linear combination of the line of the sight magnetic field component and line of sight density. With measurement of accurate bulk density from SWIRES, and its 3D reconstruction, and if heliospheric polarization measurements can be separated from other changing sources of polarization along each line of sight, it becomes possible to measure the 3D large scale heliospheric magnetic field components anywhere in the interplanetary medium. To watch these field components evolve in 3D over distances from the Sun as structures propagate outward will be another potential goal of SWIRES.

In addition to heliospheric data, SWIRES enables other measurements of astrophysical interest. The white-light observations enable studies of the zodiacal dust cloud and the extended geocorona. PERSEUS can also obtain long-term photometric brightness time series for thousands of bright stars across the sky. The analysis of brightness variations of these stellar time series supports a number of astrophysical studies, such as the search for extrasolar planets by stellar occultation; the study of eclipsing binaries, and also intrinsic variable stars; the search for optical counterparts of gamma-ray bursts, and detections of novae (.e.g., Hounsell et al., 2010). SWIRES can record zodiacal dust brightness variability and the interaction of the plasma heliosphere with this zodiacal dust. SWIRES allows observations of ion component of comet tails extending many tens of degrees from the comet nucleus, which can be used to derive estimates for the solar wind speed near the comet and along its tail.

III. INSTRUMENTAL HERITAGE AND PRESENT APPROACH

The present instrument is based upon our experience with the Solar Mass Ejection Imager (SMEI, Eyles et al. 2003, Jackson et al. 2004; 2010). We are guided further by experience with the coronagraphs on SOHO and the heliospheric imagers on STEREO. This proposal describes a minimal system, here called “SWIRES”, and designed for an 840 km polar orbit and to look close to the Sun. Figure 2 shows a sketch of a single imager “head”. This uses the current SMEI optics design, and provides a 3° × 60° field of view starting at solar elongation ε = 5° and extends out to 65°. Stray light originating from

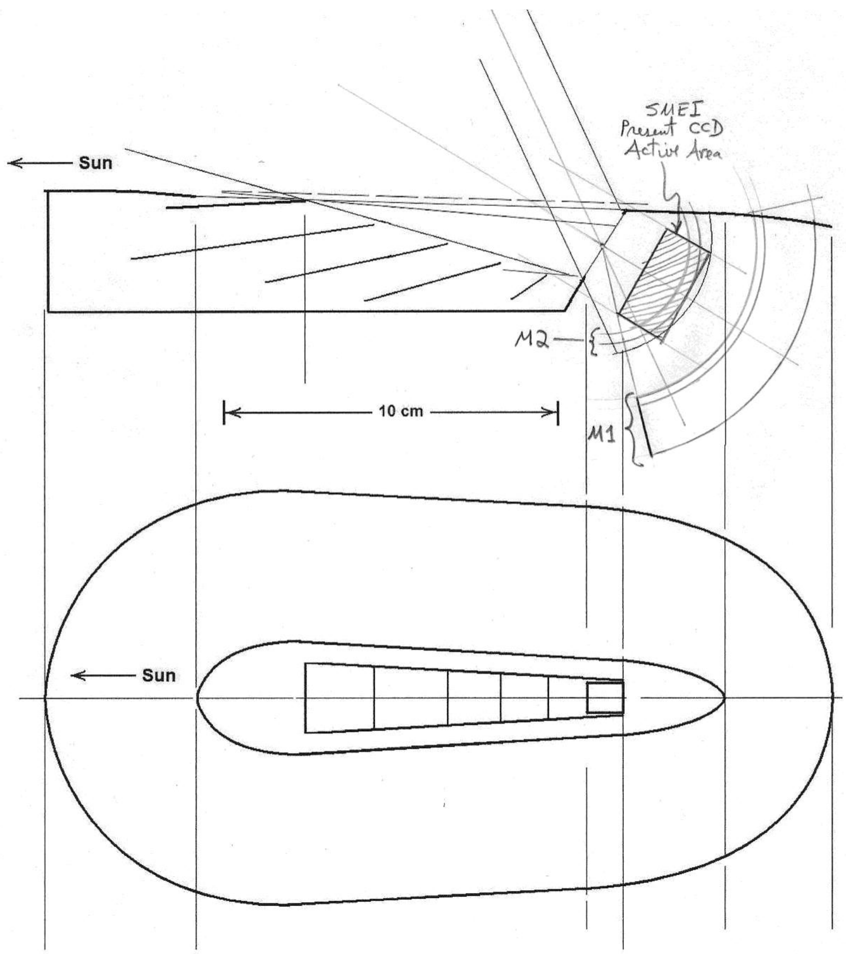

Figure 2. Sketch of a single SWIRES imager head. This particular imager views starting at 5° from the Sun, out to 65°. Stray light originating in the hemisphere below the tangent to the curved corral (dashed line) is eliminated by the corral itself. Mirrors M1 and M2 place a 3° × 60° field of view directly on the CCD detector. The system of vanes shown control contributions of stray light when the Moon illuminates within the corral.

outside of the 180° field of regard is controlled by a smooth corral which has demonstrated surface-brightness reduction in laboratory measurements of 10^{-12}, more than enough that is needed here (Buffington, 2000). This will eliminate stray light contributions directly from the Sun, and from illuminated spacecraft appendages, provided these are kept below the field of regard. Considerable mass is saved, compared with SMEI, by employing the smooth corral in place of the SMEI baffles. Some interior baffling is employed here to control scattered moonlight when the moon is within the baffle's field of regard. By adding a similar second imager head viewing from ε = 60° to 120°, i.e., viewing roughly toward the zenith, SWIRES covers most of the sky each orbit (each 100 minutes). A system with 4 heads would still cover from 5° to about 120°, and remove aurora by one pair being cocked about 30 degrees relative to the other around the Sun-Earth line.

The above approach builds upon SMEI experience, by adopting an optical design with proven performance, and with a mature data analysis sequence developed and "ready to go". The background subtraction techniques and data tables supporting them are also in place and have a well-proven performance. These analyses all require the removal of a long-term base from the imaging data. SMEI has taught us that a **successful measurement of actual heliospheric 3D densities requires** that this long term base indeed be much longer than the few hours of orbit-to-orbit differences, or even the day or so averages, that are widely used by other groups analyzing heliospheric imagery. Difference images may ease the background subtraction requirements, but do so at the expense of sacrificing larger and hence longer-term structures (Jackson et al., 2009), which are nonetheless key to understanding the overlying physical processes. Analysis of the difference images further suffers from the effects of changing perspective and evolution of the structures being observed.

The wide sky-view data and global models resulting from **SWIRES** data analysis enables characterization and demonstrates how to determine the way the Sun affects the environment of the inner solar system and even how it extrapolates to the outer boundary of the heliosphere. In addition, **SWIRES** data analysis has the unique capability to include contextual information from worldwide Earth-based solar and heliospheric instrumentation and to promote the solar and heliospheric analysis capability of the largest computer modeling centers. It is not merely the data returned that is important, but also the resulting data analysis. These combined aspects of the program bring far more resources to bear on answering fundamental heliophysical questions. To answer the fundamental questions listed earlier, **SWIRES** remote-sensing results must be combined with existing space (in situ) and ground-based observations, and the ensemble analyzed using heliospheric modeling techniques that provide focus for this experiment.

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The Importance of Fundamental Laboratory Measurements to NASA Heliophysics

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Interpretation of measurements, modeling of heliophysical phenomena, design of instrumentation, forecasting space weather, … all of these have one thing in common: their success in understanding, observing, and predicting inherently relies on our knowledge of fundamental physical parameters. The accuracy of a model of a solar or atmospheric process often hinges not so much on our understanding of the complex mechanisms involved, but on the relatively simple, but sometimes largely uncertain, knowledge of an atomic cross section, a transition probability, the temperature dependence of a photochemical reaction, or the branching ratio of a reaction. The utility of measurements of a solar eruption, an energetic input to the upper atmosphere, or the reaction of an atmosphere to variability in that input, can be significantly decreased by something as basic as the uncertainty in the transmission of a thin metal filter or the responsivity of detectors in instruments. Models of the spectrum of the Sun are insufficient at some wavelengths simply because the emissions of the highly ionized species in the solar atmosphere cannot be included because they are not known.

The above are but a few examples of basic physical parameters that are key in Heliophysics research, but are not known or not quantified to the accuracy required by the science the NASA Heliophysics program is attempting to accomplish. Many times researchers must resort to using complex heliophysical models constrained by sometimes expensive space-based measurements of heliophysical phenomena to derive the fundamental physical parameters needed to make their models work. This is a backwards situation that can result in delaying scientific advances significantly, wasting money and effort, when a relatively inexpensive series of laboratory experiments would solve the problem. It is often left to the "pure" Physics or Chemistry communities to make the laboratory measurements required to pin down these fundamental parameters; however, the motivation for these communities to do this vital research is not always there. They have their own set of priorities that do not overlap well with the needs of the Heliophysics community.

We propose that NASA set up a coordinated, clearly defined and carefully prioritized program to fund basic laboratory research in support of the vast range of heliophysical research it already funds, in other words, to provide the motivation and funding for laboratory researchers to make the measurements necessary for the NASA Heliophysics program. A survey of the different fields of Heliophysics should be undertaken to determine which laboratory measurements are the most necessary to contribute to advancement in each field. A suggested, but not necessarily complete, list of focus areas for laboratory research would include: cross sections, transition parameters, reaction rates, and branching ratios. Examples of needs in these areas are given below.

There is a need for laboratory measurements of properties of atomic and molecular species of heliophysical importance when interacting with both electromagnetic and particle radiation. The species targeted by the program should be prioritized for the different types of research. For instance aeronomical studies require understanding the absorption, ionization, and emission cross sections of O, N, O_2, N_2 and other species with respect to electron, proton, and photon impact over a broad range of energies, from photoelectrons to relativistic particle events, from X-rays to the ultraviolet, and at various interaction temperatures. Uncertainties in some of these cross sections have lead to difficulties in aeronomy research. As an example, the retrievals of geophysical parameters from space-based OI and LBH dayglow observations require knowledge of the cross sections to electron impact on atomic oxygen and nitrogen. Every time a new measurement or assessment is made of these cross sections that changes their values, vast amounts of satellite measurements and aeronomy models must also be reassessed.

The instrumentation community is hampered by lack of adequate measurements of optical properties such as the transmission of thin foil filters, the behavior of multilayer coatings on mirrors and filters, and the responsivity of various common types of detectors as the observational needs of the Heliophysics community pushes the envelope of technology to measure at different and more difficult wavelength and energy ranges. As an example, the optical properties of thin metal filters in the shorter wavelengths of the EUV and X-rays are not as well quantified as they need to be for instruments measuring, for example, solar irradiance to accomplish the accuracy that the Heliophysics community demands for its research. In the wavelength region above ~45 nm the optical properties of materials can not be described by just the properties of the constituent atoms, and atomic interactions have to be taken into account. Though this is often not a problem for basic instrument design, it is fundamental to know the optical properties of common materials used in system at these wavelengths to be able to understand and assess degradation mechanisms, and to constrain instrument and spacecraft cleanliness requirements, that have a direct cost impact on a mission.

Other examples include the fact that the solar physics community is hampered by the need for more and accurate atomic transition parameters, especially of highly ionized atoms such as Fe, Si, Mg, and so on that occur in the hot plasma of the solar atmosphere. The aeronomy community is also hampered by the fact that many important chemical reaction rates are only measured at room temperature and pressures and are only applied to the vastly different temperatures and pressures occurring in the thermosphere through uncertain extrapolations. The same is true for branching ratios. Yet our understanding of the upper atmosphere via models is greatly dependent on knowledge of these rates and ratios.

In summary, knowledge of fundamental physical and chemical parameters are necessary for the advancement of research in all areas of the Heliophysics program, yet in many areas that fundamental knowledge is not adequate. We have attempted to list only a few of the many possible examples. We suggest that NASA undertake a coordinated appraisal and targeted funding of laboratory measurements of the necessary basic parameters, giving the motivation and resources to the communities in a position to make these measurements, and, for a small investment, adding substantial value to the models, missions, and measurements of the Heliophysics program.

White Paper:

"Using KEEL Technology for Vehicle Prognostics & Diagnostics, and for Other Space Applications"

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Summary:

This whitepaper will address many space topics. The technology described can be applied horizontally in the heliophysics realm (Theory & Modeling, Innovations: Technology, Instruments, and Data systems).

This paper will address how KEEL® ("Knowledge Enhanced Electronic Logic") Technology can be used to achieve many goals described in NASA's Heliophysics Roadmap, including:

- Produce a "broader and deeper understanding of the heliophysics realm".
- Effective integration of technologies, theory, modeling and data analysis.
- Help in the effort to allow the USA to "reap the benefits both economically and intellectually".
- Advanced Information Technology: Autonomy, and computational methods and algorithms for multidimensional data analysis and visualization.

The following topics will be discussed in order to describe the broad range of applications where KEEL can be applied to current and future space needs:

- Diagnostics/Prognostics
- Autonomy
- Command and Control
- Communications
- Intelligence, Surveillance and Reconnaissance
- Unmanned Vehicles
- Information Operations/Cyber Operations
- Ubiquitous Communications and Computing Environment

After reviewing this paper, NASA will become aware of the capabilities that can be achieved through the use of KEEL Technology to deploy component solutions in order to support many types of space applications. These components (engines) are platform and architecture independent, and they are 100% explainable and auditable. NASA will understand how the use of KEEL Technology can satisfy future needs that would otherwise cost billions of dollars using conventional approaches.

General Description & Process

KEEL Technology provides a new way to process information by accumulating supporting and objecting arguments (driving or blocking signals) in order to make a decision or take an action. It includes a development environment supporting a “dynamic, graphical language” for modeling and testing human-like reasoning.

SMEs (subject matter experts) use the KEEL toolkit to design & test complex models. Refer to the diagram on the last page. When they are satisfied with the design, they use a menu item to auto-generate the code and data tables. This 3K chunk of code is then passed to the system person to incorporate in existing applications as a function call (subroutine) to “go think”. The system person simply passes Input data IN, and takes OUT the Output resultant values – to be used in their applications as decisions or actions. The SMEs can quickly model complex behaviors (code) 90% faster than by regular means (i.e. using the conventional process of creating models using domain experts, mathematicians, and software engineers).

Diagnostics and Prognostics involve the interpretation of information (or symptoms) in order to determine the cause of the problem. KEEL technology provides a mechanism to provide human-like reasoning in order to interpret information. With the results of the KEEL interpretation, information can be supplied to interested parties; control signals can be used to adapt to sensed or predicted problems; control signals can be used to trigger information logging; or to provide adaptive control. KEEL based systems can be triggered to operate whenever appropriate: polled, change of state, time-based, or continuous. When information is static one might want to process the information and create a report. When the information is continuously changing a more dynamic/adaptive system is provided.

KEEL based systems do not care where the information comes from. KEEL Engines (the encapsulation of instances KEEL Technology) are architecture independent. In closed loop systems, diagnostics can be used as part of the system. The analysis can be used to tune the system so it operates continuously. These types of systems are termed "adaptive" systems. Some adaptive systems have built in redundancy, which allows one segment that has been diagnosed with a problem to be repaired while the other segment continues the normal operation.

Autonomy

KEEL technology allows the autonomous space vehicle or subassembly to make judgmental decisions on its own. Just like humans, KEEL based systems can take direction from external sources that can change how the autonomous functionality will operate. Inputs to KEEL based systems from external sources can be given different levels of trust and can be given different levels of authority, just like human systems. Autonomous vehicles will have to respond to information by making judgmental decisions about how to trust what it sees or hears. This is just like human systems that have to be aware of possible trickery or faulty information. KEEL systems can be constructed to be flexible regarding trust, or they can accumulate trust. Both concepts will be appropriate for autonomous vehicles.

KEEL systems can react to risk. Risk assessment can be used to adjust the policy-based model operating in the KEEL engine. This could be recognized internally and it could be tuned externally. Human systems have self preservation built into them at some level. An autonomous system can have this built in at the factory and left static, or it can be tuned or controlled from external sources. KEEL based designs for the cognitive sections of autonomous vehicles allow the support of very complex systems. It would be difficult, if not impossible, to create this functionality with conventional techniques, especially when explicit auditable solutions are required.

Autonomous vehicles have to adapt to changing environmental conditions. They have to react to changing importance of information. Decisions and actions are relative, rather than binary in most cases. Autonomous vehicles are often faced with limited processor and memory requirements. KEEL based autonomous vehicles can make judgmental decisions on their own and operate completely without external intervention, or they can accept any types of external direction to be part of a larger system.

Command and Control

Everything in command and control is an "information fusion" problem. Every device, every system, and every system of systems has certain responsibilities / goals that need to be pursued using information available that may change every instant. Information is used to make decisions, take actions, and allocate resources. Every decision and action requires the fusion of multiple pieces of information whose *values* are established by other pieces of information. Each piece of information may be valued differently in the pursuit of sometimes *conflicting goals* (self preservation, collateral damage, tactical and strategic goals, and unforeseen situations). These goals may all evolve at different rates, and at different locations (*temporal data*). Systems may share information at different times, requiring *time-value-of-information* considerations. Decisions and actions may require the balancing of alternatives and allocation of resources to exert *relative* control when conflicting goals are being pursued simultaneously. The interpretation of the value of information items may diminish over time or as trust degrades. Trust, itself, is a dynamic data item that can be determined and manipulated.

Since everything is an information fusion problem to KEEL, the importance of information items can change based on any number of inter-related influences. KEEL Engines are active components that encapsulate the KEEL-based policy established by an SME and dispense control decisions and relative actions. KEEL Engines have a simple API, making them easy to integrate into any space-related platform and architecture.

To facilitate the implementation / creation of KEEL Engines, the KEEL Toolkit includes a "Dynamic Graphical Language" (DGL) that makes it relatively easy for an SME (non-programmer / non-mathematician) to capture, create, test, package, audit, and explain the complex behavioral models or policies (*how to think*). The DGL provides an easy to use, explicit means of describing adaptive policies. Utilizing the KEEL DGL to define and deploy policies can result in 90% more cost effective development practices. Also, because the same explicit policies can be distributed across systems, it should only be necessary to exchange smaller packets of information between devices. All similar devices would be able to interpret the data relative to their specific situation (*self organizing groups*). Because devices operate on "policies" rather than rules, they would know how to operate with missing information or old information. Also, as complex models are distributed to field devices, the KEEL-based support for reverse engineering of decisions and actions will support the need to continually extend the policies when needed.

The KEEL DGL can be identified as a new form of mathematical representation: a methodology for defining dynamic value and functional relationships between items. The simplicity of the language makes it relatively easy to define solutions to complex (*dynamic, non-linear, inter-related, multi-dimensional*) problem sets. KEEL DGL may be the "first" truly dynamic language. It makes use of the dynamic, interactive, graphical display characteristics common with today's computer workstations.

Policies / behavior packaged as KEEL Engines provide mathematically explicit solutions that can be deployed on any platform, and in any system architecture. It can be used in any command and control application that has the complex characteristics mentioned above. In this vein, KEEL provides a new way to process information (much like an analog computer would balance outputs to exert control), yet it can execute on conventional microprocessor / computer hardware (8 bit microprocessors and above).

Intelligence, Surveillance and Reconnaissance activities can benefit from packaging the skills of human SMEs and deploying them into space systems. KEEL is a component solution that can be applied at any level above raw signal processing. A hierarchy of KEEL Engines (localized and distributed) can interpret and fuse information allowing a more intricate strategy for controlling access to waterways. Integrating information into a "rendering" of a KEEL-based policy can be a primary tool for visualizing how and why an automated system is performing the way it is. Services integrated into the "technology package" allow an observer to understand "exactly" how a system is behaving *without requiring high levels of training*.

Unmanned Vehicles / Autonomous Systems can benefit from the small memory footprint and performance of KEEL Engines. KEEL Engines give autonomous systems a "right-brain" so they can apply judgment and reasoning as if a human was embedded in the system. They will also benefit from the ease of use of the KEEL DGL as new sensors and actuators are integrated into the system. The efficiencies provided by the KEEL DGL and KEEL Engines should greatly reduce the overall system costs as KEEL will be reducing the costs of very expensive development efforts. Unmanned systems will have *auditable* information interpretation capabilities that have never before been possible.

Information Operations/Cyber Operations will benefit from the ease of use in the creation of adaptive systems that need to be continually updated in order to respond to changing threats.

They will benefit from KEEL's platform and architecture independence and a simple API (Application Interface) that enables KEEL Engines to be integrated into new and existing systems with relative ease since they are simple class methods or function calls (depending on the target system). Tactics and strategies (human and system) can easily be created, tested, packaged, deployed, audited and explained. KEEL policies can be deployed into almost every facet of next generation space applications.

Ubiquitous Communications and Computing Environment can benefit from the ability to create policies / behavior that can be used in the M&S space, training space, embedded in devices, and demonstrated over the internet, all with one development effort because models created with the KEEL DGL can be deployed in any of C, C++, C++.NET, C#, Flash Actionscript, Java, JavaScript, Octave (MATLAB), Python, Scilab, Visual Basic, Visual Basic .NET and others without re-engineering. The "explicit" models described with the KEEL DGL greatly simplify understanding the models, which, in turn, makes them easier to extend and/or correct; ultimately leading to better and more capable systems.

Relative to **Science, Technology, Engineering and Mathematics Research**, KEEL provides a fundamental new way of defining and testing complex models of human and device behavior. Where historically humans utilized methodologies that were based on what could be "written on a piece of paper" (books, formulas, scripts), KEEL makes use of the dynamic nature of a computer screen. It allows dynamic data to be interactively defined and stimulated, thus allowing the modeler to visualize the impact of dynamically changing information as it is being defined. KEEL Technology (the KEEL Tools) also allows real-world data to be integrated into one part of a design while another part of the system is being designed (adaptive what-if scenarios / changing tactics).

Deliverables:

Step 1- One (or multiple) phone discussions which include introducing KEEL to NASA personnel using specific demos on the Compsim website.

Step 2 - A hands-on 3-day workshop will be provided to a small group of NASA personnel in Brookfield, Wisconsin in order to expose individuals to KEEL Technology and "tools" (KEEL Toolkit, KEEL Function Block Tool, KEEL Display tool, KEEL Concept Modeling tool) so that these personnel will understand that KEEL can perform many of the duties that currently require outsourcing to prime contractors. This process should allow NASA ultimately validate the cost savings that could be achieved by acquiring all rights to KEEL Technology (patent portfolio, software tools, etc).

Step 3 – Hand-over of the Technology applications and patent portfolio.

Compsim will walk through all the supporting documentation (including code review) with NASA personnel.

Full Cost: $140M – Alternatively, see " Note" below.**

Key Personnel (with Time for each):
Tom Keeley: 200 hours
Helena Keeley: 50 hours

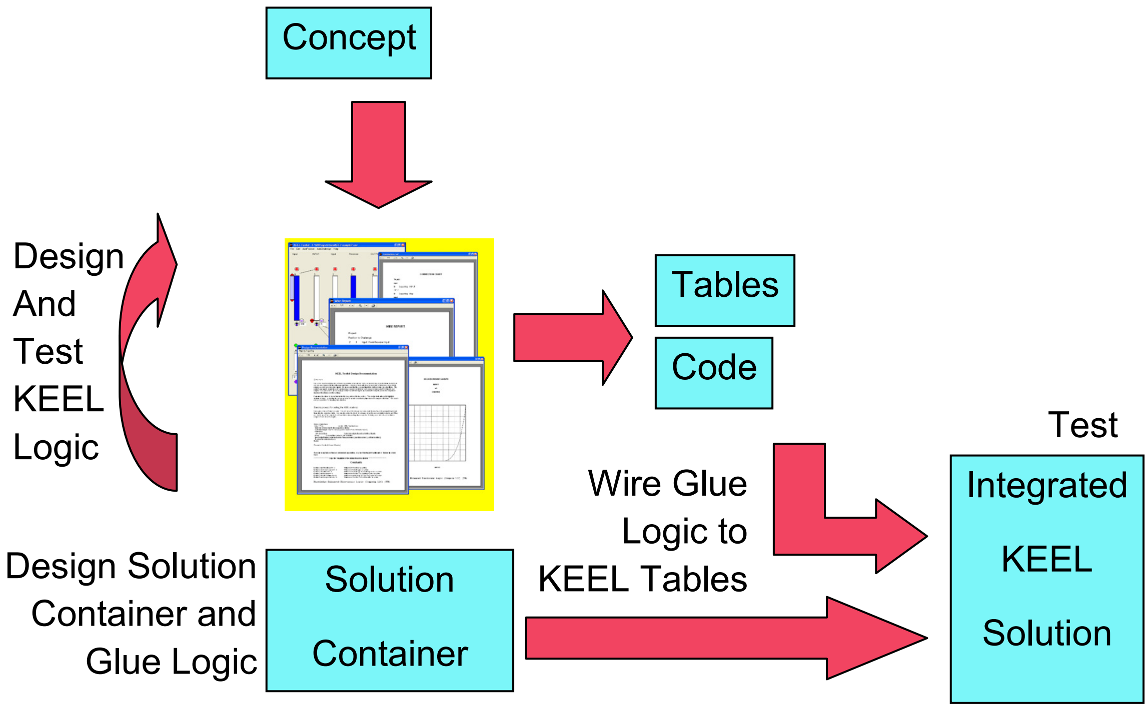
Relevant past performance on similar research projects: A broad range of demonstrations are available on Compsim's website: http://www.compsim.com – including:

- UAS related demonstrations
  - Policies for UAV interpreting target value, target risk, external threats, hiding places, damage assessment, weapon supply, collision detection / avoidance, with external control that adjusts "how the UAV is to interpret what is sees" and including "frustration" as a goal seeking approach.
- Adaptive Targeting: policy for evaluating target value while considering infrastructure damage, non-combatant and friendly forces collateral damage with remote configurable policy tuning.
- Swarm Management: Self organizing swarm with remote configuration.
- Surveillance Demonstration: Aircraft maneuver selection and control tracking moving vehicle while maintaining optimal position relative to vehicle and remote moving base station and simultaneous threat avoidance. (configurable policy)
- Profiling: How humans with historic and future emotional and economic profiles will respond to positive and negative events.
- Yerkes-Dodson / Hans Eysenck Psychological Model: How humans with different personality profiles respond to stressful tasks.
- Communications: Adaptive Network Threat Policy
- Dirty Bombs: Policies for an autonomous ship to avoid dirty bombs in varying environmental conditions.
- Mine Sweeping: Adaptive path control, detection, and response for autonomous mine sweeping equipment.

Summary of any and all anticipated deliverables to NASA: NASA will have unlimited rights to KEEL Technology including the supporting applications and a series of granted US patents.

[** Note: If NASA would prefer to license the technology for specific applications (/components), Compsim would be open to negotiating the terms.]

Development Process



Science and Mission Concept of a Holistic Ionosphere-Auroral Zone-Magnetosphere Investigation

Submitted to the Heliophysics Decadal Survey 2010

by

Andreas Keiling
Associate Research Physicist
University of California at Berkeley
Space Sciences Laboratory

Summary

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- Science problem
- Previous missions
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- Relation to other missions
- Acknowledgment

The most comprehensive auroral mission yet is outlined to address many science issues that have been raised by previous auroral missions. A necessary mission to accomplish this is a multi-spacecraft mission with a large enough number of four-point conjunctions along a magnetic flux tube. The key region for auroral processes is located at latitudes greater than 60° and in an altitude range between about 4000 km and 15000 km, the so-called auroral acceleration region (AAR). The mission has four observation points distributed along the flux tube, which is unprecedented. Three points are in situ at the top region, the middle region, and the bottom region of the AAR. The fourth point constitutes ground-based observations to determine the ionospheric electro-dynamics and optical auroral structures. This can be achieved with the following spacecraft constellation: three spacecraft each on a circular orbit with an inclination of 90° and with orbital periods of 2 hr, 4 hr, and 8hr, respectively. All orbits are in the same plane. This allows for "three-point conjunctions" every 8 hr, or three per day. In addition, many partial conjunctions will also be of interest. To connect the in-situ observations with auroral and electrodynamic structures in the ionosphere, the spacecraft will be synchronized every 24 hours ("four-point conjunctions") with ground observatories, consisting of radars, all-sky imagers, meridian scanning photometers, and magnetometers. These conjunctions will allow us to study the large spectrum of auroral forms and associated phenomena in both the nightside and dayside in the most comprehensive way yet.

Relevance **-** Contrary to popular belief many of the most basic aspects of the aurora remain unexplained. Further dedicated auroral investigations are desirable in order to expand our fundamental understanding of the Sun-Earth system.

Science Problem

There are two major modes of energy transport in the magnetosphere (Figure 1): Convective and field-aligned flows (flow refers to both kinetic and electromagnetic energy flow).

(1) Convective flow is the largest of all. Spacecraft missions such as Geotail, Cluster and THEMIS have been investigating this flow.

(2) Field-aligned flow leads to strong coupling of remote regions over short time scales. The auroral acceleration region (AAR) is coupled to the upper ionosphere and the outer magnetosphere along magnetic field lines. The intricacies of the aurora depend on this coupling. Several missions have investigated this flow (see below for more details).

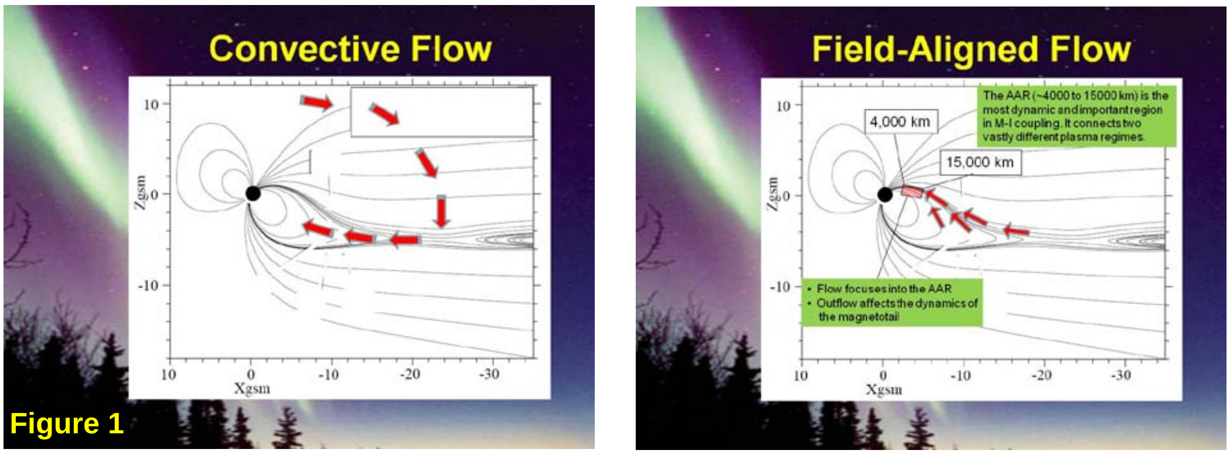


Figure 1

Shape, form and dynamic behavior of the aurora are linked to the mechanisms that accelerate the particles that cause the aurora. The auroral acceleration region, located approximately between 4000 and 15000 km altitude at high latitude (>60°), is the site of many acceleration processes. Several distinct regions exist in the AAR and have been classified as upward current region, downward current region, and Alfvénic region (Figure 2). The processes in each reagion are integral parts of the magnetosphere-ionosphere electrodynamic system and play a key role in the transport of energy and particles in space.

Processes within the AAR are driven from both the magnetosphere and the ionosphere. Therefore, both ends of the AAR need to be probed while investigating the energy flow in both directions. To obtain a better estimate of how quantities such as parallel electric fields and energy conversion processes are distributed and evolve with altitude, an observation point within the AAR is also required. Thus, we argue that at least three conjugate observation points along flux tubes are desired for an improved investigation of the AAR.

While in situ measurements of the plasma conditions are required to study auroral phenomena, it is also necessary to optically observe the aurora and its fine structure in order to identify which acceleration processes correspond to which auroral forms.

While optical imaging data obtained by ground-based and space-borne cameras have shown many types of spatial distribution of auroral forms, other types of instruments, such as magnetometers and ionospheric radars, have also been revealing drastic changes in the ionospheric conditions in association with these auroral forms. It is clear that a full understanding of auroral structures requires an understanding of the underlying ionospheric electrodynamics, which constitutes electric currents, electric fields and conductivities in the ionosphere.

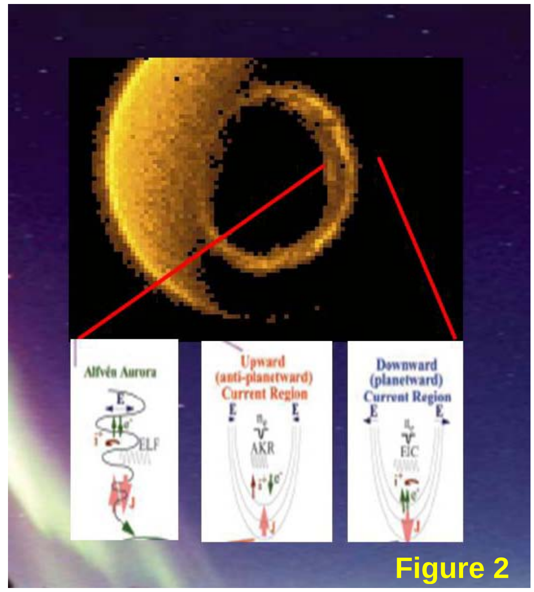


Figure 2

Knowledge of the altitude distribution of physical parameters such as the parallel electric field will also give great impetus for numerical modelers.

So far, no spacecraft mission has attempted to address all aspects mentioned above in a single, holistic mission. Occasionally, studies have benefited from fortuitous constellations using spacecraft and ground observatories from different missions or projects. We believe that a holistic approach combing all observation points mentioned above in a single mission is imperative to significantly advance the field of auroral physics. Thus, the next step forward is a dedicated, integrated ground-spacecraft auroral mission as further outlined below.

Although several successful missions (see below for more details) have provided a wealth of information, they have also told us what we need to look at next. The number of outstanding problems is large. For just one concrete example, we here look at Alfven waves. In the last decade, evidence has been collected that Alfven waves are important contributors to powering the aurora and to its fine structure. Using various single spacecraft, it has been found that most of the electron acceleration via Alfven waves occurs above 4000 km. It has also been found that large Alfven wave power arrives from the magnetotail and enters the AAR at its highest boundary. However, the exact evolution and dissipation of Alfven waves inside the AAR are unknown. Recently, interest has grown in investigating how Alfven waves precondition auroral field lines to form quasi-static potentials, and thus potentially connecting the three regions (Figure 2) that have typically been studied separately. Further, the cascading of Alfvén waves to smaller perpendicular scale sizes is proposed to occur in the AAR but is of universal interest to other astronomical objects as well, and can so far only feasibly be studied in the AAR. This list of science issues can only be addressed with suitable multipoint observation.

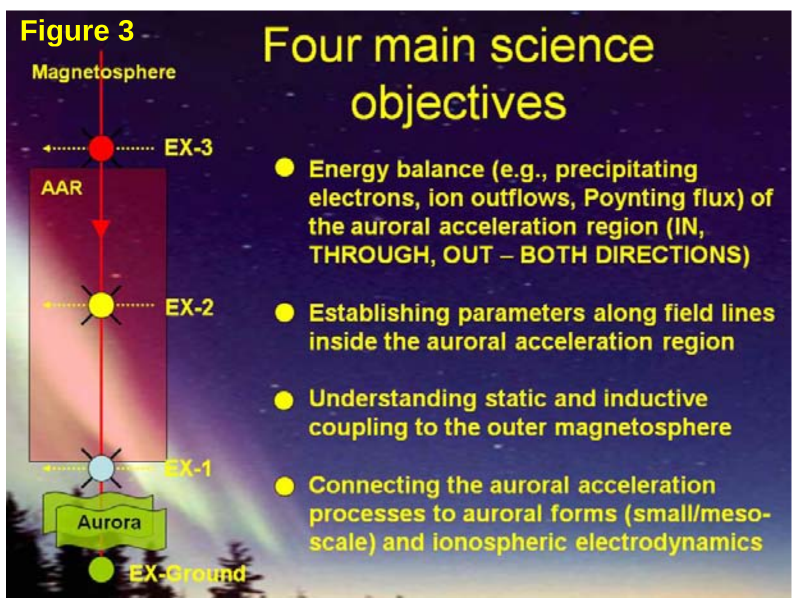


Figure 3

In Figure 3 we list four main science objectives of this mission. These objectives are representatives of a more detailed list of outstanding problems.

Previous Missions

In the past significant progress has been made to reveal the nature of the acceleration processes in the AAR by means of several auroral missions (Figure 4). All but one mission utilized single spacecraft. Recently, the four Cluster spacecraft have also crossed the AAR. Not designed for such an investigation and having lost some of its capabilities after many years of successful operation in the outer magnetosphere, Cluster nevertheless provides useful information. There is not enough space to list the accomplishments from these previous spacecraft missions. But it is without doubt that they have also created many new questions.

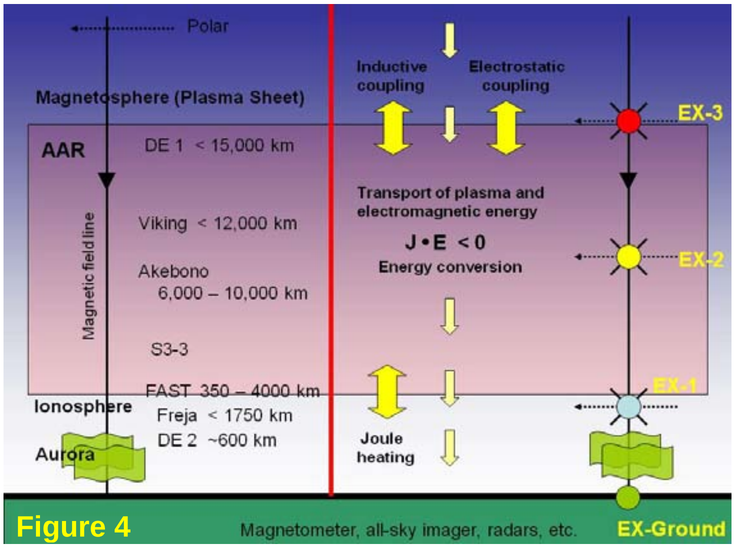


Figure 4

Since the AAR is highly inhomogeneous along the magnetic field line, it is not sufficient to use single-point measurement to study spatial distributions along auroral field lines. Since the AAR is highly time-varying it is not sufficient to use single-point measurement to study time-varying processes. Consequently, multi-point measurements are required. Below we suggest a novel approach, utilizing at least four conjugate observation points. Figure 4 shows the four observation points (EX-Ground, EX-1, EX-2, and EX-3) in relation to the AAR and other spacecraft missions.

Mission Concept

A mission with multiple spacecraft and sophisticated ground observatories is proposed. The new approach of this mission is to systematically have conjunctions along field line at the top, the middle and the bottom of the AAR, so that a detailed energy balance can be obtained of this important transition /coupling region while monitoring auroral forms and ionospheric electrodynamics with ground-based observatories. The mission concept is summarized in Figure 5.

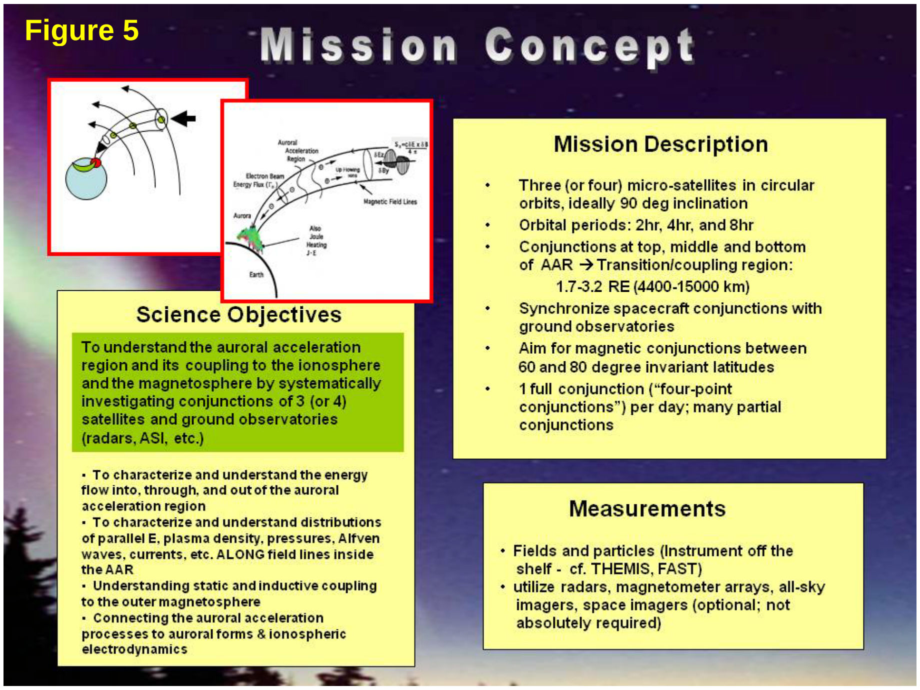


Figure 5

Orbits & Ground Observatories

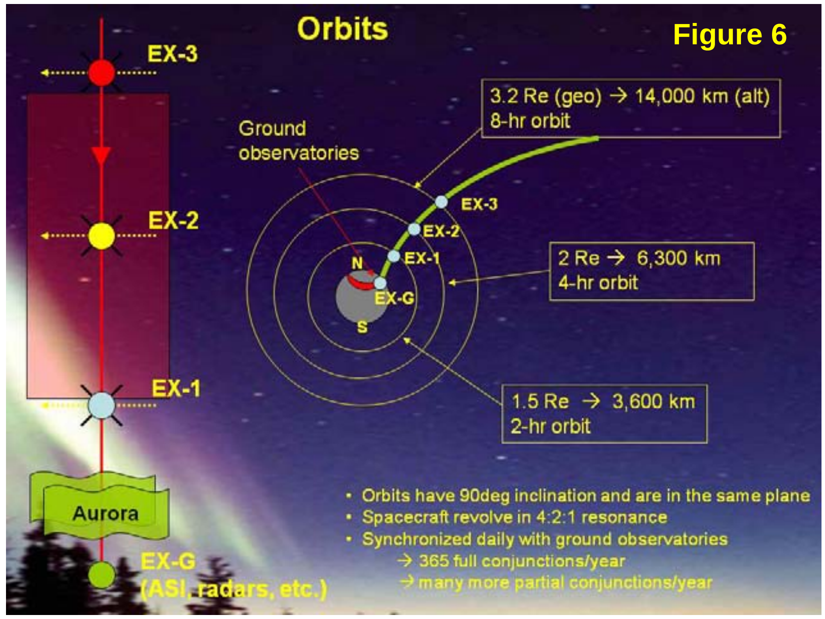
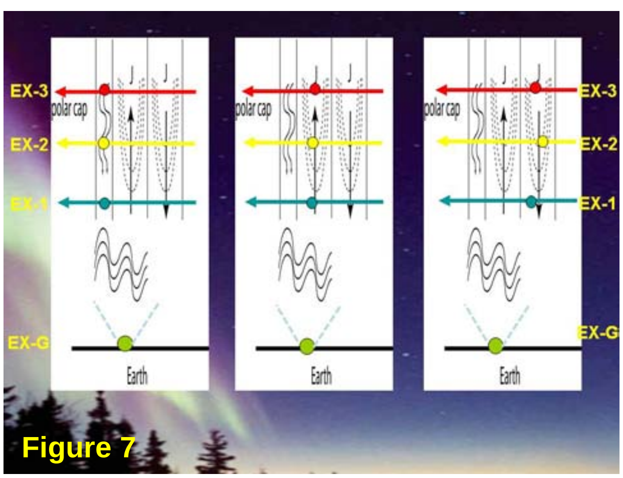
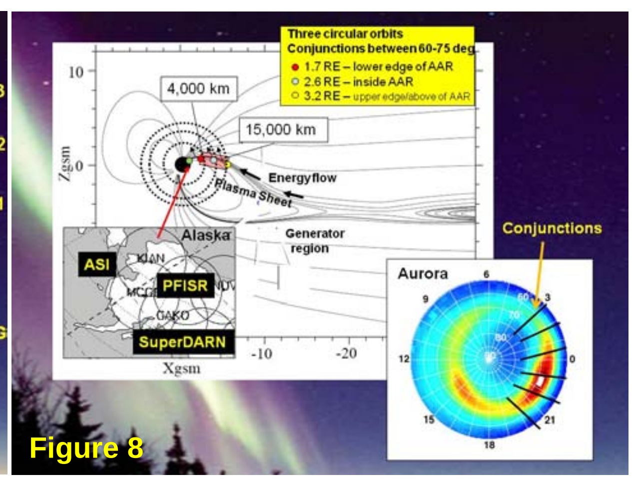


Figure 6 shows the respective orbits of EX-1, EX-2, and EX-3. They are circular with inclination (ideally) of 90°. They are in a 4:2:1 orbital resonance (similar to the three inner Galilean moons). The orbits will allow monitoring the three characteristic regions (upward current, downward current, and Alfvénic region) of the AAR (Figure 7).

Because of the yearly precession of the orbital plane, all local times will be visited (Figure 8). Hence, this configuration will allow investigating the large spectrum of auroral forms such as auroral surges, auroral spirals, auroral streamers, cusp aurora, pulsating aurora, subauroral morning proton spots, polar cap arc theta aurora, etc.

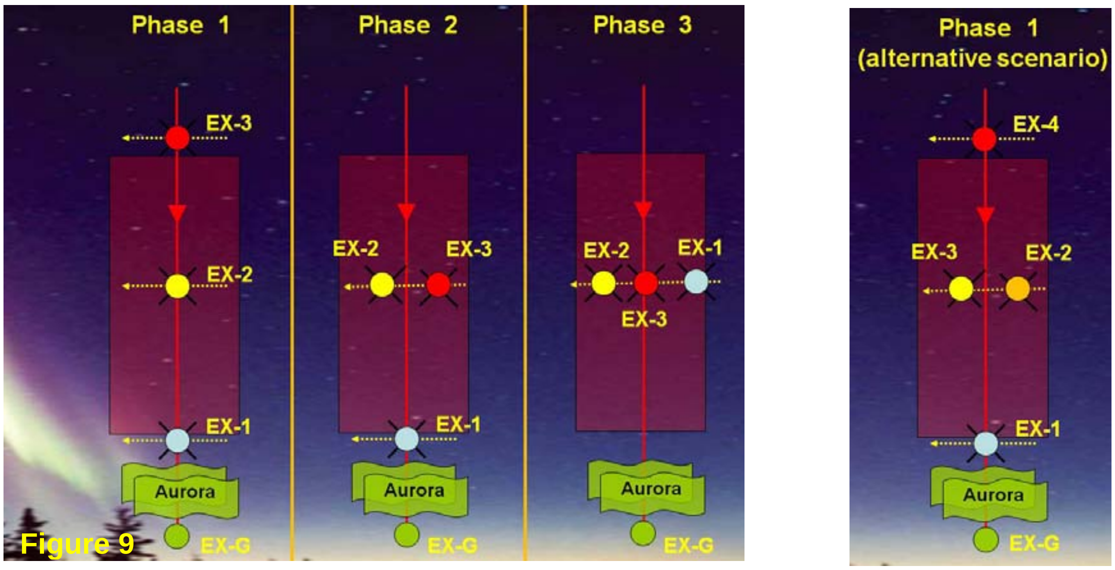
The ground observations (EX-G) are from a collection of facilities, including radars, ASIs, magnetometers, and MSPs. These observations will be synchronized on a daily basis with three-point spacecraft conjunctions. A suitable location for the ground-based observations is Alaska which already has an extensive array of facilities such as PFISR (Poker Flat Incoherent Scatter Radar), SuperDARN, ASIs and magnetometers (alternative locations are being investigated).





Mission Phases

An optional (but desirable) variation of the initial orbits (Phase 1) of the three satellites (EX-1, EX-2, EX-3) would be to move one or two satellites (EX-1, EX-3) in a pearl-on-string configuration with EX-2 as shown in Figure 9 during Phase 2 & 3. This would allow emphasizing the temporal aspect of the evolving auroral structures. Whereas Phase 2 would allow both spatial variations along the magnetic field and the temporal variations along the spacecraft trajectory, Phase 3 emphasizes the temporal aspect. Again, all three phases also greatly benefit from the simultaneous ground observations (EX-G). If additional funds are available, a constellation as shown on the right of Figure 9 is also feasible, requiring four spacecraft. The advantage is that it combines both spatial and temporal aspects from the beginning of the mission.



Estimated Costs

This mission concept was first proposed in 2007 in connection with NASA's SMEX AO. Initial feasibility studies (by Orbital Sciences Corporation) showed us that this mission cannot be accomplished with a Pegasus which was the scheduled launch vehicle. Although it was not submitted as a SMEX, the concept was further developed. The current NASA's draft Explorer AO (which is likely to allow the use of the Taurus 3110 or 3210 as launch vehicle) is more promising. Initial calculations by ATK are being done. As described above, the number of spacecraft is not limited to three but can be extended to four (or even more). Thus, launch vehicles larger than Taurus should also be considered.

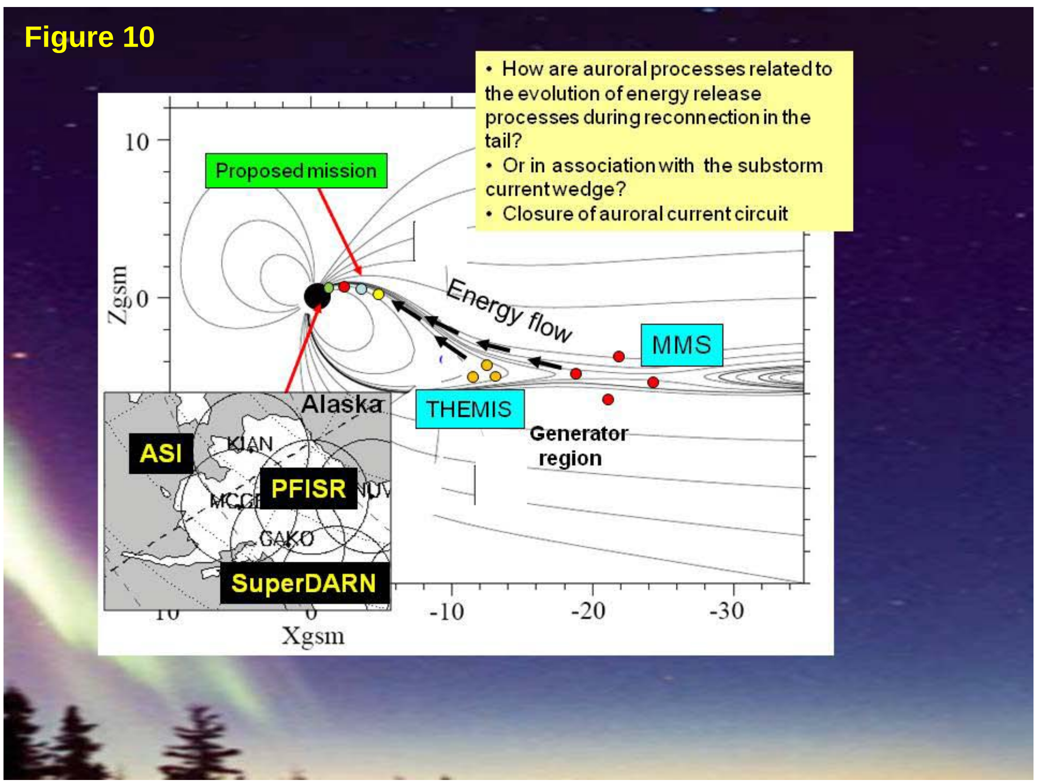
Cost-minimizing factors are: instruments are off-shelf; identical spacecraft (bus and payload). Onboard cameras are not needed but are an option. Optical ground observatories (all-sky imagers) give excellent results in connection with conjunction studies as clearly shown by the current THEMIS mission. If additional funds are available, one could consider putting a camera onboard one of the spacecraft. This however will significantly increase the design costs for the non-identical spacecraft designs.

The fourth observation point inside the ionosphere (ionospheric electrodynamics and luminous aurora) is achieved with ground-based instruments. Currently, an extensive network of magnetometers and all-sky imagers exist over Canada and Alaska (THEMIS project and CARISMA) which would be desirable to be used for this mission. In addition, radar facilities such as RISR, PFISR and SuperDARN exist to probe ionospheric electrodynamics. The existence of these facilities lowers the mission costs but adds greatly to its success.

A rough estimation of the entire mission costs would be to assume similar costs as for the THEMIS project. Total costs of the mission were $180M ($90M for the launch and $90 for management, spacecraft bus + instruments). Launch vehicle was a Delta 2. Accounting for inflation and other factors, we estimate $250M - $300M for the mission proposed here.

Relation to Other Missions

Briefly, we mention two missions that complement our proposed mission: MMS and THEMIS. MMS will investigate reconnection but it will also tell us about, for example, Alfven wave generation, ion beams, Hall currents, all of which possibly reach into the AAR. THEMIS is traversing the source region of the substorm current wedge which is a main driver of substorm-related auroral processes in the AAR. Three important science questions that could be addressed are shown in Figure 10. Although it would be an additional bonus to have such outer-magnetospheric missions available, they are by no means necessary to answer the main questions posed in this proposal.



Acknowledgement

The author thanks Orbital Sciences Corporation and ATK for initial investigations with regard to the technical feasibility of this mission.

Maximizing NASA's Science Productivity

James A. Klimchuk

November 12, 2010

This white paper concerns the science productivity of NASA's Heliophysics Science Division (HSD), and whether the existing balance in the program maximizes that productivity. Our contention is that it does not. Roughly 10-15% of the HSD budget is invested in research and analysis (R&A) activities, with the rest going to missions. We argue that this does not produce the greatest increase in scientific knowledge and understanding per dollar spent. We therefore recommend that R&A funding be gradually increased by 10% of the HSD budget to an eventual target of 20-25% of the total budget.

Let there be no mistake that NASA is a science agency. The American public, Congress, the White House, and the rest of the world all view it as such. Indeed, the visibility and importance of NASA science have grown steadily as the human spaceflight program has struggled and as global warming and space weather have come to the forefront. "The expansion of human knowledge of the Earth and of phenomena in the atmosphere and space" is the *first* objective given to NASA in the Space Act of 1958, which established the agency. Driving technological advances is an important part of what NASA does, but within NASA's science program, technology is a means to scientific progress, not the other way around.

The HSD budget is divided into two main parts: (1) developing, flying, and operating missions, and (2) funding R&A activities consisting primarily of data analysis, theory, and modeling, but also including instrument development, laboratory experiments, and ground-based observations. The total money that the HSD invests in R&A in any given year is surprisingly difficult to determine. Most R&A is funded through the grants programs: Supporting Research and Technology (SR&T), Living With a Star Targeted Research and Technology (LWS/TR&T), Heliophysics Theory (HTP), Low Cost Access to Space (LCAS; the suborbital program), and Guest Investigator (GI). The budgets of these programs are well known. What is not carefully tracked is the R&A performed by mission science teams. Total science team budgets are known, but most of this funding supports operations, basic data processing, E/PO, and other "non-science" activities.

In FY10, **only 10.1% of the HSD budget** was invested in the SR&T, TR&T, HTP, LCAS, and GI programs ($63.5M out of a total budget of $627.4M). The dollar investment has been roughly the same for many years: $63.1M, $65.6M, $60.2M, $61.8M, $61.3M, $69.4M, $63.5M in FY04--FY10, in general not keeping up with inflation (figures courtesy of P. Hertz, R. Fisher, and J. Newmark). The percentage of Heliophysics spending that these dollar amounts represent is not always straightforward to determine and compare. NASA accounting is not constant from year to year. In some years, the HSD budget includes programs that support multiple divisions (e.g., the deep space communications network, the New Millennium program, or the Astrophysics part of the Explorer program), while in other years Heliophysics is combined with Earth Science. The FY10 HSD budget of $627M quoted above is a "clean" figure that only includes Heliophysics activities.

Space missions are inherently expensive and they will naturally require most of the HSD budget. However, investing only 10-15% in R&A is a gross imbalance that does not maximize science productivity. It makes little sense to fly a mission at tremendous cost and then not adequately fund the (comparatively inexpensive) research that is necessary to get the most science from the data that are collected. Heliophysics is now a mature discipline. Gone are the days when every observation was so dramatically new and different that discoveries were routine. We have entered an **era of physical understanding**. Our field is very vibrant, and we still have a tremendous amount to learn, but future progress requires that more scientific brainpower be focused on the many unsolved problems. We need more scientists performing sophisticated data analysis, more scientists developing theoretical ideas, and more scientists running ever more realistic numerical simulations. Major advances will not come from new observations alone, but rather from a closely coordinated observational and theoretical attack. The discoveries of the future will be breakthroughs in physical understanding, and these are possible only with a strong commitment to R&A. We therefore

recommend that R&A funding be gradually increased by 10% of the HSD budget to an eventual target of 20-25% of the total budget.

Most of this growth should be in the grants programs, but increased R&A support for mission science teams and NASA centers is also important.

While we are confident that R&A is dramatically underfunded at the present time, we cannot be certain that the increase we recommend is precisely the amount that will maximize science productivity. Perhaps a larger or smaller increase would be optimum. Periodic reassessments should be made. Our recommendation is based partly on the success rates of grant proposals. Between 2003 and 2009, the overall success rate for Heliophysics proposals was 28% (http://science.nasa.gov/researchers/sara/grant-stats/). In comparison, the success rate for the entire Science Mission Directorate (SMD) in 2007-2008 was 39%. We conclude that the grants programs of the Division are considerably underfunded compared to those of the Directorate, which are themselves underfunded. Examining the data in more detail, we find that 45% of the proposals rated Very Good (VG) were not selected across the Directorate. We can infer that well over half of the Heliophysics proposals rated Very Good were not selected (data are unavailable). The ROSES NASA Research Announcement states that a rating of Very Good corresponds to "a competent proposal of high merit that fully responds to the objectives of the NRA, whose strengths fully out-balance any weaknesses and none of those weaknesses constitute fatal flaws." It further states that such proposals will be given "second priority for selection in the absence of any issues of funding availability or programmatic priorities." In other words, more than half of the VG proposals were judged to be of high scientific merit but were not selected because of inadequate funds. Another interesting statistic is that considerably more of the Directorate-wide proposals rated Very Good/Good (VG/G) or higher were rejected than were selected. Again, the picture is likely worse for Heliophysics. This is compelling evidence that the program is grossly out of balance.

Ideally, the R&A budget would grow because the HSD budget grows, but this is not a realistic expectation in the current economic climate. In a zero-sum world, the R&A budget can grow only if the mission budget shrinks. As disappointing as this may seem, it is the obvious choice for maximizing science productivity. Furthermore, we suggest that the perceived impact on missions would be rather small. NASA launched 21 Heliophysics missions between 1995 and 2010 (14 between 2000 and 2010)---an average of one new mission every 9 months. The proposed funding increase for R&A could be fully accommodated if the mission launch rate were to decrease slightly to one new mission every 10 months. Would this be noticeable?

Having argued that the overall R&A funding should increase, we now address two specific grants programs that are especially valuable and merit special augmentation: **Supporting Research and Technology (SR&T)** and **Low Cost Access to Space (LCAS)**. The Heliophysics Science Division faces two crucial challenges: How do we develop the new science ideas and new technologies that will be the foundations of future missions? How do we train the next generation of scientists? SR&T and LCAS play vital roles in meeting both of these challenges. SR&T has long been the birthplace of new theories, methods, and technological innovations. The motivation for many missions, as well as the flight instrumentation, can be traced directly back to SR&T research. Numerous examples are given in the document "Supporting Research & Technology in Solar & Heliospheric Physics" which was prepared by the Solar and Heliospheric Management Operations Working Group (SH-MOWG) for the 2001 Assessment of NASA's Space Science Research and Analysis Program. This document also discusses the important role of SR&T in funding plasma experiments, laboratory spectroscopy, and ground-based observations that support NASA science. Perhaps the greatest testimonial is that the research of Gene Parker was funded almost exclusively by the SR&T program, and his contributions to our understanding of Heliophysics easily exceed those of entire missions.

Low Cost Access to Space (rockets and balloons) is another vital program that has been woefully underfunded and deserves special attention. It is the training ground for young experimentalists, where they can get hands-on experience that is not feasible when developing hardware for expensive, must-not-fail missions. LCAS is also the proving ground for emerging technologies. Before a new technology can be flown on a mission, it must achieve a certain technical readiness level (TRL), again because failure is not tolerated. Rockets and balloons are the only inexpensive way to prove spaceflight worthiness.

In conclusion, NASA is a science agency and has an obligation to the American taxpayer to maximize its science productivity. Heliophysics is an exciting yet mature discipline in which future discoveries will be primarily in the form of new physical understanding. This requires a much stronger commitment to research and analysis (R&A). We recommend that R&A funding be gradually increased by 10% of the HSD budget to an eventual target of 20-25% of the total budget. We furthermore encourage NASA to recognize the especially important roles of the SR&T and LCAS grants programs, as it maintains a balanced portfolio of small programs, critical mass efforts, targeted research, and undirected research.

This white paper is endorsed by the following individuals:

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DECADAL SURVEY WHITE PAPER

The importance of ground-observations and the role of distributed arrays in Polar regions

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This white paper describes the importance of high-latitude ground-based observations and, in particular, the importance of instrument development, distributed arrays of instruments and multi-instrument observations. This paper specifically concerns smaller instruments or suites of smaller instruments, as opposed to facility-scale observatories.

1 Introduction

Energy transfer from the magnetosphere to the ionosphere and upper atmosphere involves dissipation and feedback, processes that are readily (if not only) observed using ground-based instruments. Clearly, the near-Earth space environment is a complex, coupled system with interactions from the macro-scale (e.g. solar wind driven magnetospheric convection) to the micro-scale (e.g. wave-particle interactions) all contributing to the global response to energy input from the Sun and solar wind. Because of this complex interplay, a proper understanding of the AIM system requires comprehensive ground-based observations 1) distributed in order to observe over a wide range of spatial and temporal scales (in both hemispheres), and 2) including multi-instrument observations to show how processes are coupled.

Our current state of knowledge of the AIM system has evolved to a level such that further advancements require measurements be acquired in a significantly more comprehensive manner than in the past. Indeed, as single-satellite missions have been replaced by formations of satellites, ground observations likewise need to evolve to distributed systems. Increasingly, addressing some of the most stubborn outstanding questions requires a multi-disciplinary approach involving multiple arrays of ground-based instrumentation, coordinated studies with spacecraft and various theoretical tools and modeling.

Observations in Polar regions

As particles and waves propagate from the magnetosphere to the ionosphere and upper atmosphere, they inevitably reach the polar regions, guided by Earth's magnetic field lines. This white paper is focused on observations at latitudes mapping to Earth's radiation belts and higher, extending to the polar caps. Of course, AIM coupling certainly includes effects at lower latitudes, so the focus on higher latitudes in this paper is arbitrary, in some sense.

Because the relative orientation of Earth's dipole axis and spin axes are not co-located, polar observations in the Arctic differ from those in the Antarctic and support three fundamentally different types of observations. First, understanding the basic differences in inter-hemispheric effects is an essential part of understanding AIM coupling in general. Second, different magnetic field perspectives are accessible in opposite hemispheres provides different perspectives on observations (described further, below). Finally, stations in both hemispheres are needed to support various satellite missions, especially those at high inclinations.

In the Arctic, observations are most often supported in Alaska and Canada, which provide excellent an platform for observing auroral phenomena. The southern portion of Canada would be an excellent platform from which to observe radiation belt dynamics, though instrumentation there is currently inadequate for this purpose.

Other regions of interest include Greenland, where a comprehensive suite of instruments (including an Incoherent Scatter Radar) have been operating in Sondrestrom for nearly 20 years. Sondrestrom is located near an invariant latitude of 75°. In addition to the instruments in Sondrestrom, DMI supports a meridional chain of fluxgate magnetomters. Further east, high latitude observations are also routinely acquired on Svalbard, with stations spanning roughly 2° ILAT, at approximately the same ILAT as Sondrestrom.

Antarctica, on the other hand, provides very different capabilities as an observing platform. Essentially, it provides a vast expanse of real estate to support a range of types and sizes of arrays (ranging from L $\sim$ 4 to the polar cap). In the northern hemisphere, the terrain is interrupted by various bodies of water and so no such broad regions exist. Although the deployment of remote observatories to arbitrary locations in Antarctica is challenging, recent successes have shown that it is feasible and can work well.

Antarctica also provides uninterrupted periods of darkness with relatively little cloud cover. Earth's magnetic field orientation is such that the polar cusp and polar cap can be observed in continuous daylight or darkness if instruments are deployed to the correct locations. In addition, Antarctica provides access to the auroral zone in darkness across all magnetic local times.

2 The unique capabilities of ground-based observations.

In general, the importance of ground-based observations are described as follows:

1. Ground-based observations provide continuous measurements of the state of the AIM (e.g., ionospheric currents, waves, winds, particle precipitation etc). Such measurements enable monitoring of the synoptic state, spatial variability, and time evolution over extended periods, thus providing substantial context for rocket, balloon, and satellite missions.

2. Spatially distributed measurements are critical in order to separate spatial and temporal geophysics. Such distributed observations complement rocket, balloon, and satellite flights by providing extensive coverage in both time and space.

3. Measurements of base-state geophysical parameters (e.g., such as neutral winds or height resolved ionospheric parameters) are of critical interest yet are difficult to measure from orbital or sub-orbital platforms. For example, flight versions of incoherent scatter radars, Fabry-Perot interferometers, and lidars - though the latter two instrument types have been flown - are typically expensive, and are limited in capability due to mass and power restrictions.

4. It is usually logistically easier and more cost-effective to deploy ground-based instruments as needed on a campaign basis. To wit, many ground-based instruments and instrument installations are relocatable.

5. It is easier to leverage the capabilities of existing ground-based instrumentation to support new projects or missions. Put another way, this means that the monetary and time costs associated with ground based facilities can be spread across multiple missions.

6. Ground based instruments are (relatively) easy for a human technician to access, to operate, or to repair. This means that they don't have to be developed to the same level of autonomy and robustness that is required of a fight instrument; ultimately translating into substantially lower costs for the same nominal capability.

7. Ground based deployments provide opportunities to test new instrument concepts and offer the ability for system upgrades as new technologies are able to be implemented. For example,

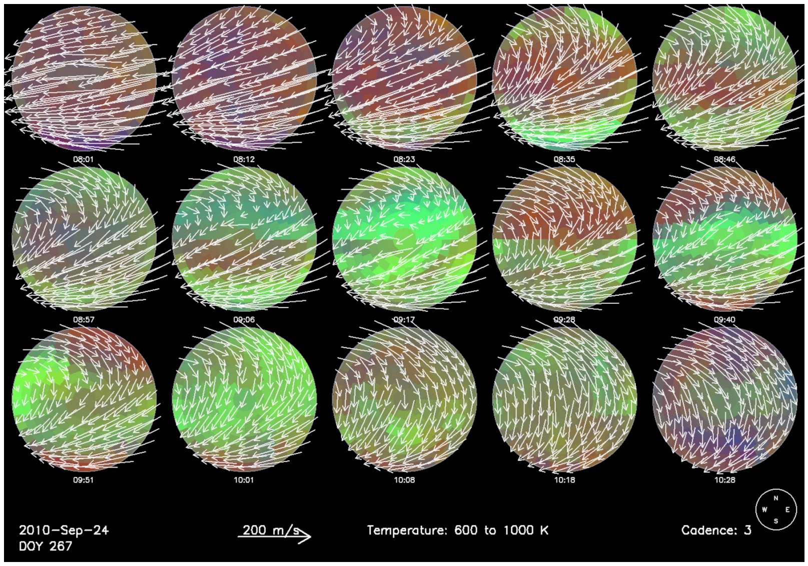

Figure 1: This plot shows the evolution of F-region thermospheric winds over Alaska, acquired with an imaging Fabry-Perot spectrometer. Background colors depict temperature (blue through red hues) and 6300 brightness (green hues).

many ground-based Fabry-Perot interferometers have exchanged photomultiplier tubes with CCD cameras, thus extending their lifetimes on the order of decades.

Below, we present three illustrative examples in order to demonstrate effective 1) new instrument capabilities, 2) results from a conjunction of distributed ground and satellite observations, and 3) distributed, conjugate observations that reveal an apparent dependence of substorm evolution on ionospheric conductivity.

Fabry-Perot observations of neutral winds and temperatures. Figure 2 shows an example of the time evolution of the F-region neutral wind field as seen by a University of Alaska ground-based imaging Fabry-Perot spectrometer. Ionosphere-thermosphere coupling is a fundamental aspect of AIM, yet there is no space mission that will be launched in the near-term that could match the ability of the imaging FPS instrument to resolve how the wind field evolves in both space and time.

Note that this figure is presented at reduced time resolution and only shows every third wind map. The vectors map to a region that basically covers Alaska, with background colors that depict temperature (blue through red hues) and 630 nm brightness (green hues). Note how the wind field completely changed direction during the 2.5 hour time period shown, and how it was far from uniform during the transition.

Evidence of substorm injections reaching the ionosphere at very high-latitudes. The second example we discuss illustrates how combinations of ground and satellite data can provide new insights into fundamental processes of the AIM system. Using Antarctic high-latitude data acquired remotely, *Lessard et al.* [2009] present results from a study of substorm injections. The main conclusion of the paper is that substorm-injected energetic electrons can precipitate to the ionosphere near the open-closed field line boundary in the late morning hours. The implication of this result is that injections models must take drift-shell splitting into account in order to reliably

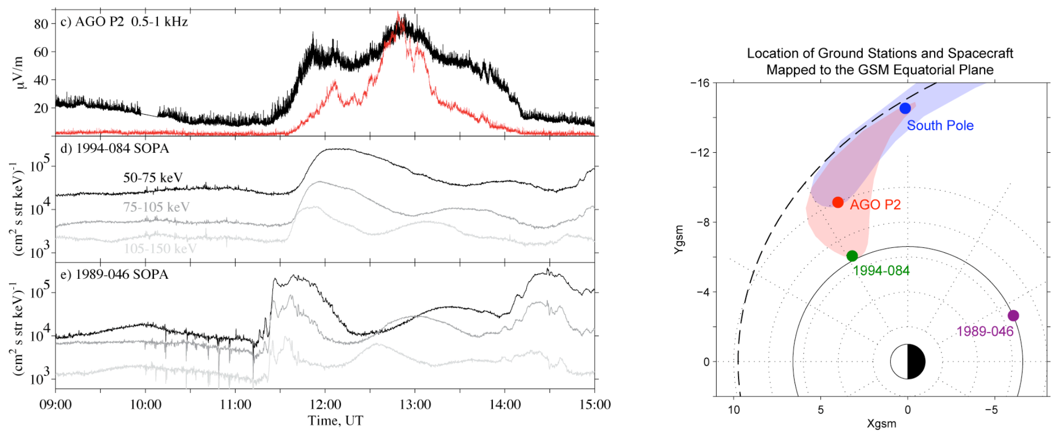

Figure 2: a) Top panel shows chorus observations from AGO P2 and the South Pole (in red), interpreted as ionospheric signatures of energetic electron precipitation. The bottom two panels show energetic electron injections from the SOPA instrument on two geosynchronous spacecraft, 1989-046 and 1994-084. b) The locations of LANL satellites and ground stations during the injection, mapped to the equatorial magnetosphere. Substorm injections were observed in-situ by the satellites and with riometer and VLF data on the ground to show that injections reach the ionosphere near the open-closed field-line boundary, i.e., at latitudes much higher than predicted by models.

predict injection dynamics.

In the model of X. Li and collaborators, the earthward dipolarization of the magnetic field results in an inductive electric field from Faraday's Law. The dawn-dusk component of the electric field, which also propagates earthward, can cause the charged particles to move earthward, following the motion of the **ExB** drift, although the inclusion of particles only with pitch angles of 90° means that this model does not address drift-shell splitting effects and so no migration to higher latitudes can result from this model. *Zaharia et al.* [2004] also incorporated a time-dependent, non-dipolar model, but still concentrate on observations at geosynchronous orbit (and addressing only pitch angles of 90°). Finally, similar work has been carried out by *Birn et al.* [1998] and *Birn et al.* [1997], using a 3D MHD code and addressing all pitch angles, but again targeting geosynchronous observations (propagation to the ionosphere is not considered).

The right side of Figure 2 shows the locations of the LANL satellites, as well as the locations of the South Pole and the AGO P2 observatory in Antarctica, mapped to the equatorial ionosphere during the injection. The left side of the figure shows VLF chorus observations from AGO P2 and the South Pole (in red), interpreted as ionospheric signatures of energetic electron precipitation. The bottom two panels show energetic electron injections from the SOPA instrument on two geosynchronous spacecraft, 1989-046 and 1994-084. Data and modeling show that the injected electrons reach the ionosphere very near the open-closed boundary.

While this paper demonstrates the scientific value of combining space- and ground-based observations, the irony is that the data were acquired by chance, to some degree, in the sense that the injection occurred at a time when the various stations were ideally positioned in MLT.

This example demonstrates the capabilities of combining satellite observations with data from the ground, yet it also points out the need for improved ground coverage. Indeed, an appropriate

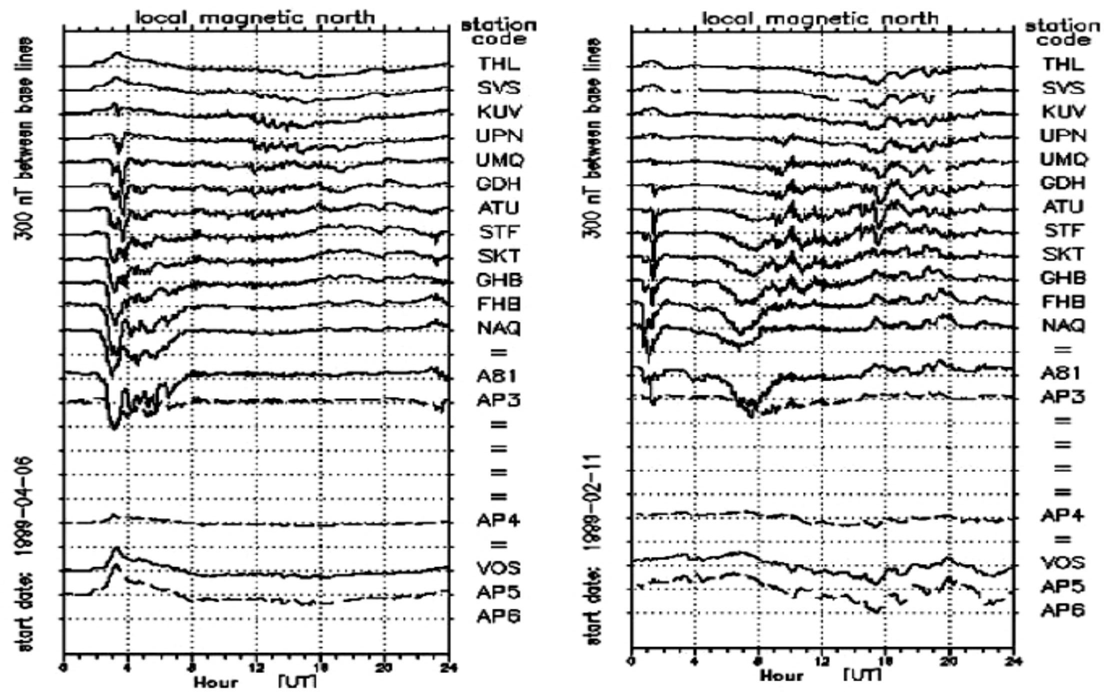

Figure 3: (left) A conjugate magnetic substorm that leapt deep into both the northern (Greenland west coast) and southern (approx. 40 degree magnetic meridian) polar caps during equanox (02 - 02 UT, April 6, 1999). (right) A conjugate magnetic substorm that leapt deep into the northern (winter) polar cap but developed only at auroral latitudes in Antarctica (summer, 01-02 UT February 11, 1999).

array of ground stations would provide much more comprehensive observations of the injections, thus providing

Distributed observations of high-latitude substorm conjugacy. Finally, this third example is presented because it illustrates the importance of distributed, conjugate measurements. On the other hand, it also shows the impact of gaps in coverage, as observations in the Antarctic are marginally adequate at best

In the conventional view of substorm progression, bright auroral features and hard electron precipitation expand rapidly poleward in the midnight sector and reach latitudes well above the typical location of the nightside oval, often accompanied by westward and eastward movements. The maximum poleward extent of substorm precipitation effects can easily reach latitudes of 75° magnetic latitude, and can sometimes extend beyond 80°. See *Gussenhoven* [1982]; *Craven and Frank* [1991]; *Weatherwax et al.* [1997] and *Mende et al.* [1999] and references therein for morphological descriptions of high-latitude substorms.

In terms of particle precipitation, one similarity in conditions shared by many high latitude substorm events is relatively high solar wind velocities. *Weatherwax et al.* [1997], using riometer data, found that of 24 substorm events seen at high latitude, all occurred when $V_{sw} > 700$ km/s. A necessity for high solar wind speed conditions in order to see substorms at high latitudes was reported by *Sergeev et al.* [1979] based on observations made at Vostok station, Antarctica.

The propagation of substorms to high latitudes was investigated by *Papitashvili et al.* [2002], who studied a number of high-latitude substorms using data acquired in Antarctica and Greenland in 1999-2000. Taking advantage of conjugate measurements, albeit with limited coverage, these authors were able to show that substorms (as observed with fluxgate magnetometers) that occurred over a dark ionosphere routinely propagate to higher latitudes than those over sunlit ionospheres, suggesting that ionospheric conductivity plays a critical role in this evolution.

To illustrate the result, Figure 3 (from that paper) shows two examples of magnetometer data from both hemispheres (the upper part of each panel shows Greenland data; the lower panels show Antarctic data, as sparse as it is). The panel on the left shows data from an event that occurred with both hemispheres in darkness; the electrojet signatures are clear in all magnetometers at 0200-0400 UT, indicating that the substorm reached high latitudes in both hemispheres. The panel on the right, on the other hand, shows data from February 11, 1999, when the northern hemisphere was dark and the southern high-latitude region was sunlit. Electrojet signatures are clear in the Greenland data, but absent from the Antarctic data. In their paper, the authors show results form a statistical study of nearly 600 events, confirming the fact that this is a valid result.

3 Summary

This paper describes the need to support improved ground-based observations that are necessary in order to obtain closure on outstanding AIM problems. These improvements include instrument development and the increased use of distributed and multi-instrument observations.

As the trend in satellite missions has evolved towards the use of *multi-spacecraft* observing platforms that support *increasingly advanced instruments*, a parallel evolution is needed with regard to ground-based observations. Indeed, the current state of knowledge has advanced to the point where single satellites or isolated ground-based observations do not typically provide significant new information. Clearly, the need for distributed arrays and/or multi-instrument observations is critical for making progress in the next decade.

We emphasize, in particular, the importance of these observations in polar regions, since these are the regions where solar wind energy is largely deposited. We therefore highlight the following points regarding ground-based measurements for the next decade:

1. We support the development of new and/or improved ground-based instruments, whether such improvements incorporate new techniques, new technology, lower power, enhanced data transfer, remote power systems, etc.

2. We support the development of distributed arrays, which are becoming increasingly important as answers to outstanding problems effectively move the remaining questions to higher levels of complexity, thus requiring better spatial and/or temporal resolution. Collaborative efforts that involve satellite missions are especially important.

3. We support the use of multi-instrument platforms in order to provide comprehensive observations, to provide context for focused observations and to provide a broader perspective in general.

4. We support improved coordination between ground- and satellite-based missions. Ground-based observations provide contextual information, can often resolve spatial-temporal effects and reveal the most basic information about the state of the ionosphere. This is critical in order to understand coupling processes in the AIM system.

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The Determination of the Effects of Major Impact on
Global Geophysical and Geologic Parameters.

L.M Lewis

Introduction

In the year 1996 the mineral coesite was found and confirmed by x-ray analysis to be associated with the SiO_2 suite of orthorhombic quartz to cristobolite to trydimite to coesite in Potter Co. Texas (Lewis, 1997). The detection of that suite supplied additional evidence the region had been i9mpacted in the geologic past and allowed the astounding conclusion which claimed the Panhandle of Texas and Eastern New Mexico and environs as a probable site of the K/T impact.; much larger than had been anticipated. The sum originating data (Lewis, 2004) also defined the impact as of highest order, capable of initiating both fission and fusion reactions, creating an extensive ejecta blanket, as well as creating other phenomena observed in the field and in thin section. That work opened a window of opportunity for decades of multidisciplinary research

Proposal for Continuing Effort

It is proposed the following continuation of that work:

1) The continued definition of the geophysical and geologic expression of impact.

2) The continued study of the origin and makeup of the impacting body.

3) A study of the effects of the impact on regional tectonics.

4) A study of the effects of impact on global geophysical phenomena.

5) A study of the effects on climatic patterns and the biosphere.

In order to determine the influence on climatic patterns as well as global geophysical parameters, it is also proposed a study of solar/galactic conditions (polar positions, magnetospheric conditions, etc.) before and after impact. The comprehensive study of all positions and conditions at the time of impact should produce a better understanding of the role impacts have played in Earth's history as well as establish a means to predict future catastrophic events.

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Energetic Particles from a highly Inclined Constellation (EPIC)

Xinlin Li, Drew Turner, Weichao Tu, and Cora Randall, LASP/U. of Colorado at Boulder

1. Overview

We propose a space mission, EPIC, to conduct coordinated observations of energetic particles in the near-Earth space environment. EPIC will work in conjunction with existing missions to answer the following questions: **(1) How solar flare location, magnitude, and frequency relate to the timing, duration, magnetospheric penetration, and energy spectrum of solar energetic particles (SEPs) at Earth, (2) How the loss rate and energy spectrum of Earth's radiation belt electrons evolves, and (3) How do these energetic particles affect the chemistry and dynamics of Earth's middle and upper atmosphere**. These questions are across multiple disciplines in solar, magnetospheric, and atmospheric physics and have profound space weather implications.

2. Mission Concept

EPIC includes the Relativistic Electron and Proton Telescope integrated little experiment (REPTile), which will measure energetic protons and electrons including SEPs from the Sun and particles from Earth's radiation belts. To achieve the science objectives listed above, multiple-REPTile instruments need to be in LEO with a minimum altitude of 450 km and minimum inclination of 60°, while a higher altitude and inclination orbit would be preferred. Ideally, we propose to put nine REPTiles on three such LEOs, separated by 120° in longitude of their ascending nodes, with three REPTiles uniformly distributed on each LEO, as shown in Figure 1. Such an orbit formation can be achieved in two ways: (1) a constellation of CubeSats, carrying REPTile as the primary payload, and (2) REPTile as secondary payload on a group of other LEO satellites, such as the CICERO (**C**ommunity **I**nitiative for **C**ontinuing **E**arth **R**adio **O**ccultation).

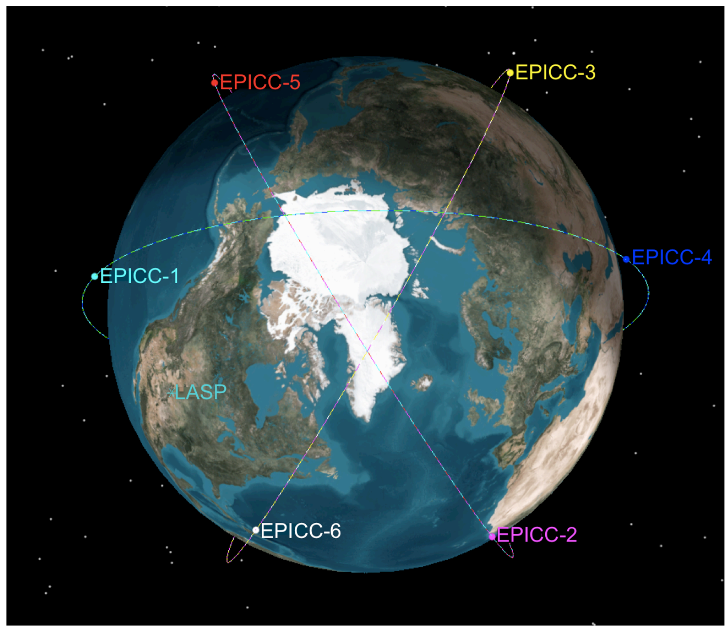

Figure 1: Satellite Tool Kit model showing orbit configuration for mission concept case (1) consisting of 9 CubeSats in three different polar orbits. Orbits shown here are 600 km altitude, circular orbits, and along each orbit, the three spacecraft are each separated by 120°. Note, spacecraft 7-9 are behind the Earth as shown here.

REPTile is a miniaturization of the Relativistic Electron and Proton Telescope (REPT) currently being built at the Laboratory for Atmospheric and Space Physics (LASP) for the NASA/Radiation Belt Storm Probe (RBSP) mission, which will send two identical spacecraft into a low inclination, geo-transfer orbit in 2012. REPTile is designed to measure directional differential flux of energetic protons, 10-40 MeV, and electrons, 0.5 to >3 MeV. The instrument design is modifiable to be able to measure different energy ranges. Energetic particle measurements from REPTile will be used in conjunction with flare measurements from other spacecraft, e.g., NASA's Solar Dynamics Observatory (SDO, in operation)-Extreme Ultraviolet Variability (EVE) and NOAA's GOES-Solar X-ray Imager (GOES-SXI), to investigate the correlations between flare parameters such as strength and location and SEP characteristics such as particle flux, energy spectrum, and cutoff latitude. Such coordinated observations have the potential to provide a basis for advance warning of SEP penetration at specific locations:

valuable information concerning their impact on Earth's atmosphere and space weather. Relativistic particle measurements from REPTile will also be used in conjunction with other spacecraft measurements, such as GOES and RBSP spacecraft, to address important questions concerning Earth's radiation belts, which also have an important impact on Earth's atmosphere and space weather.

One major benefit of having multi-point measurements is to increase the spatial and temporal resolution for measurements of the precipitating electrons and SEPs. Concerning the outer radiation belt electrons, the precipitation can be bursty, especially during the main phase of magnetic storms, and can have local time dependence since different waves having been observed to be prominent at different local times (e.g., EMIC waves in dusk and chorus waves at dawn). With our proposed constellation, the three satellites on one orbit could pass through a localized precipitation region three times per orbit rather than once per orbit by a single satellite. The three LEOs separated by 120° in longitude (4 hr in local time) ensure full local time coverage with a 4 hr separation, and the orbits achieve full longitude coverage every 4 hours due to the Earth's rotation, instead of half a day from a single orbit. Because of its low altitude orbit, with three REPTile instruments per orbit on three different LEOs, EPIC will measure outer belt electrons 36 times in one orbital period, ~1.5 hr, or about 576 times in a day. The multiple-point measurements are essential to better determine the rates and the spatial and temporal variations of the precipitation loss of the outer radiation belt electrons.

3. Science Gains

Science Questions:

(1) How do the flare location, magnitude, and frequency relate to the timing, duration, and energy spectrum of SEPs reaching Earth?

(2) How does the energy spectrum of radiation belt electrons evolve and how does this evolution relate to the acceleration and loss mechanisms?

(3) How do SEPs and radiation belt electron precipitation affect the upper atmosphere

Solar Flares and Solar Energetic Particles (SEPs): Solar flares are very violent processes in the solar atmosphere that are associated with large energy releases ranging from 10^{22} J for sub-flares, to more than 10^{32} J for the largest flares [Priest, 1981; Woods *et al.*, 2006]. The strongest support for the onset of the impulsive phase is due to magnetic reconnection of existing or recently emerged magnetic flux loops [Aschwanden, 2004, and references therein]. Reconnection accelerates particles, producing proton and electron beams that travel along flaring coronal loops. Some of the high-energy particles escape from the Sun to produce SEP events, which will be measured at Earth by REPTile. The particle beams that travel deeper into the solar atmosphere produce impulsive phase flare X-ray emissions.

Statistically, both the probability of observing energetic solar protons near the Earth as well as the maximum flux values observed are strongly dependent on the size of the flare and its position on the Sun. Belov *et al.* [2005] analyzed over one thousand SEP events with energy >10 MeV measured at GEO in the period from 1975 to 2003 and found that more than half of these events could be reliably related to X-ray flares. Energetic particles near the solar disk center are known to have more dramatic impacts on Earth than those near the solar limb. Measurements of these X-rays are made by SDO-EVE and/or GOES-SXI and will be used to identify flares for comparative studies with REPTile SEP measurements.

Evolution of the Energy spectrum and Precipitation rate of Radiation belt electrons: Relativistic electrons (100s keV to multiple MeV) trapped in the magnetosphere, often referred to as "killer electrons" due to their potential damage to spacecraft subsystems and to astronauts in space, have their largest variations during magnetic storms. Figure 2 shows measurements of selected radiation belt electrons and protons by the Solar, Anomalous, and Magnetospheric Particle Explorer (SAMPEX), ~550 km altitude and 82^{o} inclination, from launch to the end of 2000 together with the sunspot number and the Dst index. The outer belt electron measurements exhibit variations on a range of time scales, including solar cycle, seasonal, and solar rotation time scales and geomagnetic storms.

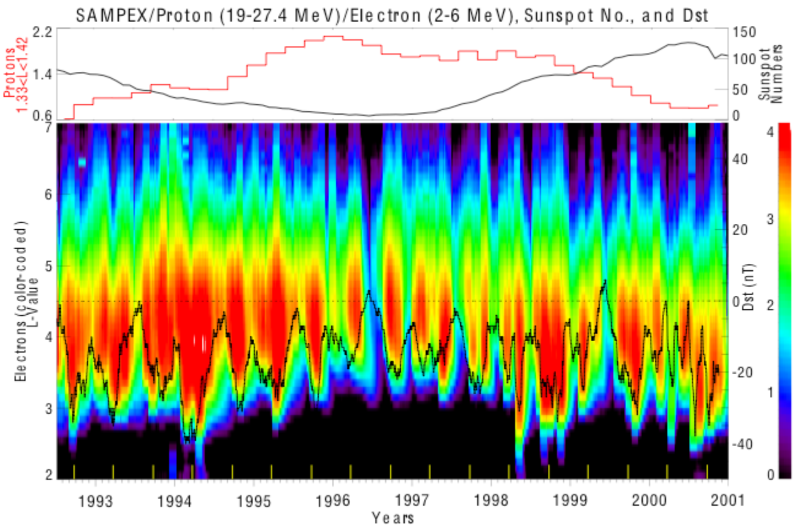

Figure 2: Selected measurements of protons (#/cm^2-s-sr-MeV) and electrons (#/cm^2-s-sr, in bins of 0.1 L-shell) by SAMPEX, with sunspot number and Dst index for the same period. The L-shell is the radial distance in R_E at the equator if Earth's magnetic field is approximated as a dipole. The Dst index for the same period is superimposed as a black curve. The sunspot numbers are window-averaged over a 9-month period and the electron and Dst index is window-averaged over a 30-day period in order to show the overall feature. The yellow vertical bars on the horizontal axis are marks of equinoxes. *(Adapted from Li et al., 2001)*

Instruments onboard SAMPEX, though a wonderful mission for its original objectives, were not designed to make accurate measurements of the outer radiation belt electrons. Those instruments have two major limitations: i) they have very large view angle (>57°), and ii) they lack the differential flux measurements. With multiple REPTiles, we will have much better measurements of the electrons in terms of pitch angle resolutions and energy spectrum. Most importantly the multiple-point measurements will enable us to separate the spatial and temporal variations.

Acceleration Mechanisms: How the outer radiation belt is formed in the Earth's magnetosphere remains one of the most intriguing puzzles in space physics. For some time, it was thought to be well understood at least in its general outlines. However, recently the paradigm for explaining the creation of the outer belt electrons has been shifting from one using almost exclusively the theory of radial diffusion to one emphasizing more the role of waves [Horne *et al.*, 2005; Chen *et al.*, 2007; Bortnik and Thorne, 2007; Li *et al.*, 2007; Tu *et al.*, 2009], presumably chorus whistler waves, in the heating of radiation belt electrons. A key proof of this new paradigm is to see how the energy spectrum of the radiation belt electrons evolves. A hardening spectrum (higher energy electrons increasing faster than lower energy electrons) at a given location would support the theory of in situ heating of the electrons by waves. EPIC, with three separated LEO and three REPTile on each orbit, will measure outer belt electrons 36 times in one orbital period, ~1.5 hr. With its differential flux measurements, REPTile will be able to provide the critical information of the evolution of the electrons' energy spectrum.

Loss Mechanisms: Since the overall structure of the radiation belts and their variability are controlled by the competition between source and loss processes [Reeves et al., 2003], knowing the loss rate is a necessary condition to understand the underlying acceleration mechanisms and completely understand the outer radiation belt dynamics. It is understood that precipitation into the atmosphere is the main loss mechanism of outer belt electrons, but it is not clear if the electrons slowly diffuse into the loss cone (that means the electrons will reach low altitude, say 100km, and collide with neutral particles and get lost) or in a bursty way. Some waves, like electromagnetic ion cyclotron waves, can only cause pitch angle diffusion of the electrons, sending some electrons into the loss cone. Other waves, like whistler mode chorus waves, can cause energy diffusion as well as pitch angle diffusion. These waves have their local time dependences. With its finite field view angle, multiple-REPTile can detect the local pitch angle distribution of the outer belt electrons and observe the evolution of the pitch angle distribution, determine the total precipitation loss and how much loss occurs at different local times with higher time resolution.

SEPs and Radiation belt electron precipitation impact on the Atmosphere: Energetic particle precipitation (EPP) from SEPs and the Earth's magnetosphere has been suggested to be an important process affecting space weather and middle and upper atmospheric chemistry and possibly dynamics.

Concerning space weather, energetic particles can play a role in the degradation or even disruption of communications, degradation in the accuracy of the highly relied upon Global Positioning System (GPS), and surges in our power lines on the ground that could lead to widespread blackouts. In the atmosphere, EPP affects atmospheric odd hydrogen (HO_x), odd nitrogen (NO_y) and ozone (O_3) through dissociation, ionization and subsequent chemical processes [e.g., Thorne, 1980; Randall et al., 2007]. By direct deposition of energy and impact on radiatively active gases NO and O_3, EPP can influence temperatures from the thermosphere to the stratosphere, and thus possibly circulation [e.g., Jackman et al., 2006; Gabriel et al., 2007]. Stratospheric processes can influence the troposphere, impacting weather and climate [e.g., Baldwin et al., 2007; Perlwitz et al., 2008]. Still unknown is the degree to which EPP might thus indirectly affect climate. In turn, tropospheric perturbations such as might originate from anthropogenic climate change can be communicated to the middle and upper atmosphere [e.g., Fomichev et al., 2007], thereby altering the atmospheric response to EPP through relevant meteorological pathways.

Although it is known that the most significant effects of EPP on the middle atmosphere occur via EPP in the polar regions, the particle energies that are most "geoeffective" – that is, the energies that contribute most to atmospheric effects – are still unknown. It is believed that the most important effects occur through polar chemistry changes from the upper troposphere to the upper stratosphere. Those changes might occur after relatively low energy EPP where NO_y is created in the polar thermosphere but then descends to the stratosphere during the winter [e.g., Randall et al., 2005; Seppala et al., 2007]. Higher energy particles will create NO_x directly in the stratosphere; this NO_x will immediately be available for ozone depletion. Jackman et al. [2009, and references therein] have shown that SEPs have both short and long-term effects on the middle atmosphere. Energetic protons and electron precipitations detected near the polar regions can be used in conjunction with meteorological assimilation data sets and atmospheric measurements from such satellite instruments as the Atmospheric Chemistry Experiment and Aura microwave limb sounder (or follow-on instruments) to understand the interactions between the energetic particles and the atmosphere. Ideally, future measurement strategies will include measurements of polar night NO_x from the stratosphere to the thermosphere, since EPP-induced changes in NO_x trigger subsequent atmospheric responses. EPIC, with its differential flux measurements from multiple-REPTile, would provide an essential database for the study of the magnetosphere-ionosphere-atmosphere interactions as well as their space weather applications.

4. Payload

Students enrolled in a Space Hardware Design course, which is co-taught by Prof. Li, designed the REPTile sensor that is shown in Figure 3. This sensor is currently being manufactured to serve as the primary instrument aboard the Colorado Student Space Weather Experiment (CSSWE), a CubeSat mission supported by the NSF. The sensor comprises a stack of silicon solid-state detectors in a telescope configuration enclosed in aluminum and tungsten shields. A collimator sets the field of view to a circular cone of <50°. A 0.5 mm beryllium (Be) disc located at the detector-end of the collimator (shown in light blue in Fig. 3) stops electrons below ~400 keV and protons below ~10 MeV (from continuous stopping distance approximations and Geant4 simulations described below). The solid-state detector stack is made up of 4 separate detectors with a total thickness of 1 cm and can measure electrons in four energy channels starting at 0.5 MeV to >3 MeV and protons in four channels with energies from 10 MeV up to 40 MeV. Suitable silicon detectors have been developed for the REPT instrument and are available from Micron Semiconductor. A 3.5 mm thick tungsten (W) layer of shielding surrounds the detector stack (dull green in Fig. 3), which is further encased by an outer aluminum (Al) layer that is 5 mm thick (dull blue-gray). This shielding effectively stops energetic electrons below ~20 MeV and

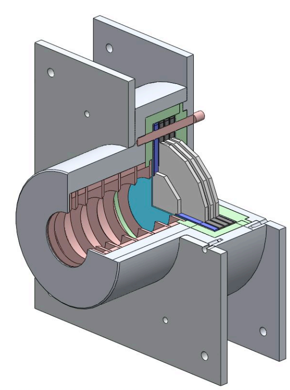

Figure 3: REPTile instrument cut-away view. Here, different materials are shown in different colors. See text for component description.

protons below ~90 MeV from entering the detector stack from the sides, while thicker tungsten shielding (extra 2 mm) in the back further increases the particle energy needed to penetrate the stack and significantly improves the signal to noise ratios. Higher-energy (>15 MeV) electron flux at LEO and most protons with sufficient energy to penetrate the shields will pass through both the shielding and the sensor leaving only minimal deposited energy. The collimator acceptance angle, cross section, and the Be-window limit the flux at the detector to rates manageable by a standard electronics design, nominally on the order of 10^4 /s rising to ~$5x10^5$ /s during enhanced events. The detectors can have a time resolution of 10s of millisecond, which are fast enough to resolve microburst of the precipitating electrons.

Geant4 has been employed to estimate REPTile's performance taking electron scattering and energetic particle shield penetration into account. Geant4 is a software toolkit developed by scientists at CERN to simulate particle interactions in matter, and it is extremely accurate for statistical studies, making it ideal for simulating the instrument performance. It should also be noted that the REPTile design is adaptable to be effective over different particle energy ranges. By changing the thickness of the Be window, the collimator geometry (which determines the instrument's geometric factor and thus significantly affects the total count rates on the detectors), and the detector thicknesses, REPTile's energy bins can be adjusted in either direction, to measure either higher or lower energy electrons and protons.

5. System

The EPIC CubeSat system will be based heavily on the CSSWE CubeSat (see Fig. 4). CSSWE is specifically designed to be compliant, without exception, with the CubeSat requirements to ensure proper integration with the California Polytechnic CubeSat P-POD deployment system. The 3-unit (3U) standard configuration is comprised of a spacecraft bus built with commercially available subsystems and with the instrument provided by the University of Colorado.

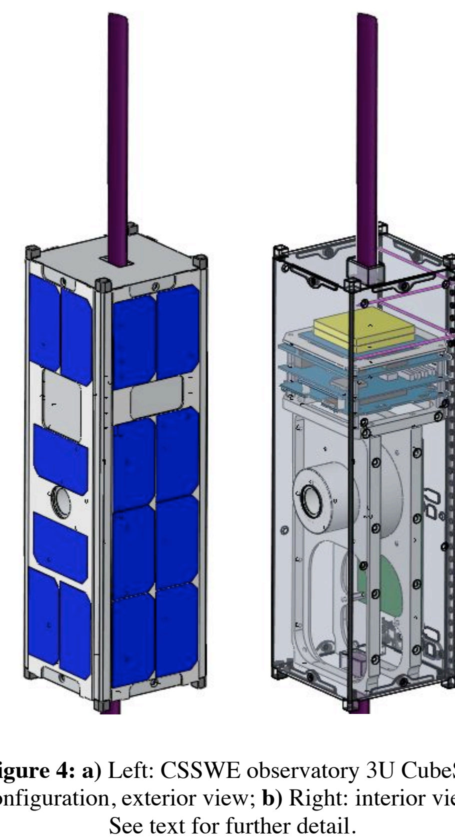

Figure 4: a) Left: CSSWE observatory 3U CubeSat configuration, exterior view; **b)** Right: interior view. See text for further detail.

Following CSSWE, each CubeSat for EPIC will use the standard CubeSat 3U structure commercialy available from Pumpkin Inc. The internal structural support will include a "skeleton frame" upon which the majority of the internal components are attached so that they can be easily removed as one unit for ease of testing and integration. Externally, the solar cells are mounted onto printed circuit boards that clip onto the side panels using commercially available parts with heritage. This entire structure has undergone extensive finite element analysis and will undergo pre-launch vibration testing for CSSWE. CSSWE stresses simplicity in its system configuration and implementation. It's subsystems consist of a command and data handling (C&DH) board, electrical power subsystem (EPS), communications (COMM), science (REPTile), and a passive magnetic attitude control subsystem (PMACS). C&DH consists of a single electronics board with a MSP-430 microcontroller and flash memory. The C&DH, EPS, and COMM boards interface electrically and mechanically via a standard 104-pin connection such that they stack vertically inside the CubeSat. There are only three data interface protocols used throughout the system, which are all standard: I^2C, SPI, and AX.25, with I2C used for most subsystem interfacing and SPI and AX.25 used primarily for COMM. EPS consists of the solar cells, battery stack, and EPS board which regulates the power and allocates it appropriately throughout the system. The COMM subsystem consists of an electronics board with its own microprocessor to interpret signals from the ground network and a single monopole antenna, which operates at 433 MHz. For EPIC, which will have to handle higher data rates, S-band (~2 to 4 GHz) can be employed. S-band communications schemes have heritage from many previous CubeSat missions. The antenna gain pattern for CSSWE is optimized to work with the PMACS system, which passively aligns the spacecraft with Earth's local magnetic field along the orbit. This is implemented using a permanent bar magnet fixed to the bottom end-cap and a series of hysteresis rods. The bar magnet interacts with Earth's local field to create a torque, while the hysteresis rods provide the damping torque resulting in an attitude in which the long axis of the CubeSat settles to within around ±5 degrees of the local field direction within a few days of orbit insertion. An onboard magnetometer is used to confirm the PMACS performance. Finally, concerning REPTile (discussed in detail above), the instrument is positioned such that the aperture normal is approximately 90° to the local field, and the instrument electronics board lies behind the instrument. This board processes the signals from the REPTile detectors and tallies the count rates, which are sent to C&DH via an I^2C interface.

CubeSat systems like the one described here are low-mass, low-power, and low-cost. The total system mass of CSSWE is ~3 kg for the entire spacecraft, which fits into a total volume of $32\times10\times10$ cm^3. CSSWE's total power requirement is less than 5 W of orbit averaged power, which is provided by the solar panels to keep the system power positive. The EPIC spacecraft will be based heavily on the CSSWE design and heritage. Also, these CubeSat systems are extremely low-cost relative to other space missions, and this is discussed in more detail in the next section.

6. Estimated Cost

For the CSSWE mission (one 3U CubeSat), the cost cap is $1M, not including launch and integration. For the proposed EPIC mission, building nine identical CubeSats should cost less than $9M, and assuming launch is $3M per orbit (3 on each orbit), the total cost of EPIC in mission concept case (1) will be less than $20M. For mission concept case (2), we only need to build nine payloads (i.e. REPTile instruments) and the interfaces with the primary missions; thus, the total development and launch cost should be much lower than those for case (1), particularly if the launch costs are mostly covered by the primary payloads. However, this will really depend on what kinds of mission opportunities are available. At LASP, student mission operators are employed to great success. For concept case (1), three students can be employed part time (one third time each for a total of $50k) to help with the communications and data handling. For concept case (2), these assistants are unnecessary, as the primary payload operators should handle the communications and data initially. For either concept case, a full time employee running at half time for six months (~$40k) will be required for mission management, data handling, processing, and quality control. For both cases, there will be operational expenses for ground network access. All of these expenses are roughly estimated and totaled in the table below.

Expenses	Concept Case (1)	Concept Case (2)
Systems development	< $9M	< $4M
Launch	$9M	$9M
Operations (post-launch labor)	$90k	$40k
Ground network expenses	$100k	$100k
TOTAL	**< $18.2M**	**< $13.2M**

7. Mission Viability

The EPIC mission as described here satisfies the decadal study criteria, as follows. Using multi-point measurements of energetic particles at LEO, EPIC would be able to address important scientific questions concerning solar flares and the characteristics of their resulting SEP events, Earth's radiation belt electrons and the evolution of their source and loss mechanisms, and how both these solar and magnetospheric energetic particles affect atmospheric ozone depletion. These areas have previously been recognized as high priority NASA and NSF. To properly address these questions, EPIC would require collaboration with other missions and systems, including RBSP, SDO-EVE, GOES, and space-borne microwave limb sounders. Concerning societal benefits, EPIC would address questions important to the mitigation of space weather risks from energetic particles, as well as ozone loss which may be a contributing factor in global warming. EPIC would be able to provide society with these valuable scientific benefits from a constellation of instruments at a total mission cost of less than $20M. Furthermore, the REPTile instrument and CubeSat systems (if required) are already under development for the CSSWE mission. Considering all this, EPIC would provide scientific data that is beneficial to both the scientific community and society as a whole from an inexpensive and practicable space mission.

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Solar Polar Imager: Observing Solar Activity from a New Perspective

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Abstract

Our current understanding of the Sun, its atmosphere, and the heliosphere is severely limited by the lack of good observations of the polar regions. The Solar Polar Imager mission, in a 0.48-AU orbit with an inclination of 75º, targets the unexplored polar regions and enables crucial observations not possible from lower latitude perspectives. The orbit is achieved using a solar sail, a technology now being demonstrated in space by the Japanese IKAROS mission. Observations from a polar vantage point will revolutionize our understanding of the mechanism of solar activity cycles, polar magnetic field reversals, the internal structure and dynamics of the Sun and its atmosphere. Only with extended (many day) observations of the polar regions can the polar flows be determined down to the tachocline where the dynamo is thought to originate. The rapid 4-month polar orbit combined with a suite of *in situ* and remote sensing instrumentation further enables unprecedented studies of the physical connection between the Sun, the solar wind, and solar energetic particles. Moreover, SPI serves as a pathfinder for a permanent solar polar sentinel for space weather prediction.

I. Introduction

Our understanding of the Sun, its corona and the solar wind has been revolutionized by observations from past spacecraft such as Yohkoh, ACE, Ulysses, TRACE and SOHO and from current spacecraft such as RHESSI, Hinode, STEREO and SDO. Yet as we learn more about the Sun from these missions and the complement of ground-based telescopes, the need for information from the polar perspective only increases. The Solar Polar Imager (SPI) defined by this study utilizes a solar sail to place a spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 75º (Figure 1), enabling high latitude studies and extended direct observation of the solar poles. A very similar mission concept POLARIS was submitted to the ESA Cosmic Vision call (Appourchaux et al., 2009). Observing the polar regions of the

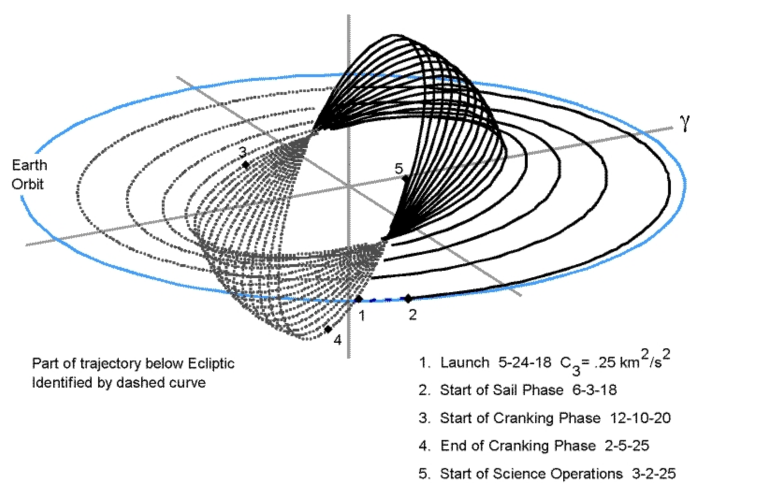


Figure 1 SPI trajectory for 2018 launch. The final science orbit at 0.48 AU is in a 3:1 resonance with the Earth at a final heliographic inclination of 75°.

Sun with a combination of a Doppler-magnetograph and coronal imagers yields opportunities for major new science. Local helioseismology measurements of polar supergranulation flows, differential rotation and meridional circulation, and magnetograms will allow us to understand the mechanisms of the polar field reversals and also the factors determining the amount of the magnetic flux accumulating in the polar regions, which is a primary precursor of the future sunspot cycles. Correlation between measurements of the Doppler signals in the polar regions with disk center measurements from the ground or from near-Earth spacecraft, such as SDO, should enable the determination of flows deep within the Sun. When Doppler and magnetograph observations are coupled to total solar irradiance monitoring, UV spectroscopic observations and *in-situ* particle and field measurements, SPI will substantially enhance our knowledge of the root causes of solar variability. While Solar Orbiter will provide a glimpse of the polar regions, it does not have sufficient viewing of the polar regions to achieve the major scientific objectives defined for SPI.

Unique remote sensing and *in situ* observations made possible by this orbit (Figure 1) include

- Measurements of the time-varying flows, differential rotation and meridional circulation in the polar regions of the Sun down to the tachocline
- Measurements of the polar magnetic field and its temporal evolution
- Monitoring of Earth-directed coronal mass ejections from high latitudes
- Observations of active regions over a significant fraction of their lifetimes
- Measurements of the variation in the total solar irradiance with latitude
- Measurements of chromospheric and low coronal outflow velocities as a function of structure and latitude
- Measurements of the variation in the magnetic fields, solar wind and solar energetic particles (SEPs) with latitude at constant distance from the Sun

2. Mission Concept

In order to determine the polar flows down to the tachocline, long (many days) nearly continuous observations of the polar regions are required. ***This is the driving requirement for defining a mission with an orbit inclination of 75°.*** The SPI mission uses a solar sail to reach this nearly polar solar orbit. By first spiraling in towards the Sun, the radiation pressure is increased so that "cranking" to higher inclination is more efficient. The final radius is chosen to be 0.48 AU because (a) its orbital period is exactly 1/3 of Earth's (3:1 resonance) allowing an unobstructed Earth-spacecraft line for telecommunications and (b) interpretation of solar wind data is simplified closer to the Sun because of shorter interaction time and smaller velocity dispersion.

The SPI Visions Mission concept, as defined in the NASA-funded Vision Mission Study (Liewer et al., 2009) requires a characteristic acceleration of 0.34 mm/s^2 to achieve the 3:1 resonant science orbit at 0.48 AU. Given the leading technology concepts under development for solar sails, this results in a sail of approximately 8.5-14 g/m^2 with physical edge lengths of about 150-180 m. The material used for the sail "sheets" was assumed to be an aluminum-coated polyimide or aluminum-coated Kevlar-reinforced kapton. The mission concept summarized in this paper represents the baseline concept developed for the SPI Vision Mission study that has been fully documented in a report to NASA. Since that study, there have been major advances in the technologies for solar sailing, demonstrated in the laboratory and now also in deep space by JAXA's recent IKAROS mission. The advances in the development of solar sail technology is the subject of separate white paper entitled "Solar Sail Propulsion: Enabling New Capabilities for Heliophysics" submitted by Johnson, et. al. The cost of the baseline mission in the NASA Vision Mission study, inflated to FY10 dollars, is $800-$900M, including launch vehicle.

3. Science Goals

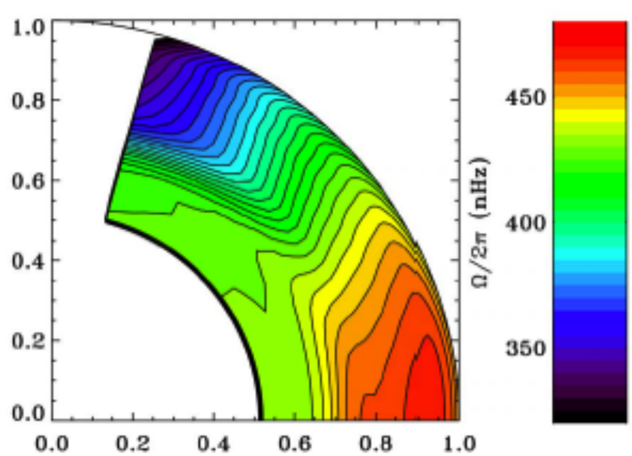
In the study, a refined set of mission science objectives were developed that can only be achieved because of the observations enabled by SPI's short period, highly inclined polar orbit. The primary scientific questions to be answered by the mission are:

1. *What is the relationship between the magnetism and dynamics of the Sun's polar regions and the solar cycle? More specifically, what is the mechanism of the polar magnetic field reversals, and why does the polar field determines the strength of the future solar activity cycle?*
2. *What is the 3D global structure of the solar corona and how is this influenced by solar activity and coronal mass ejections?*
3. *How are variations in the solar wind linked to the Sun at all latitudes?*
4. *How are solar energetic particles accelerated and transported in radius and latitude?*
5. *How does the total solar irradiance vary with latitude?*
6. *What advantages does the polar perspective provide for space weather prediction?*

These mission objectives address every aspect of the first challenge and first key questions of the NRC Decadal Report on Solar and Space Physics: *"Understand the structure and dynamics of the Sun's interior, the generation of solar magnetic fields, the origin of the solar cycle, the causes of solar activity, and the structure and dynamics of the corona."* It may also contribute to the fifth challenge: *"Developing a near-real time predictive capability for understanding and quantifying the impact on human activities of dynamical processes at the Sun…"* (SPI goal 6). The mission also address many of the objectives in NASA's 2009 Heliophysics Roadmap: F2) Particle acceleration and transport; F4) Creation and variability of magnetic dynamos; H1) Causes and evolution of solar activity; J2) Capability to predict the origin, onset, and level of solar activity; and 3) Capability to predict the propagation and evolution of solar disturbances.

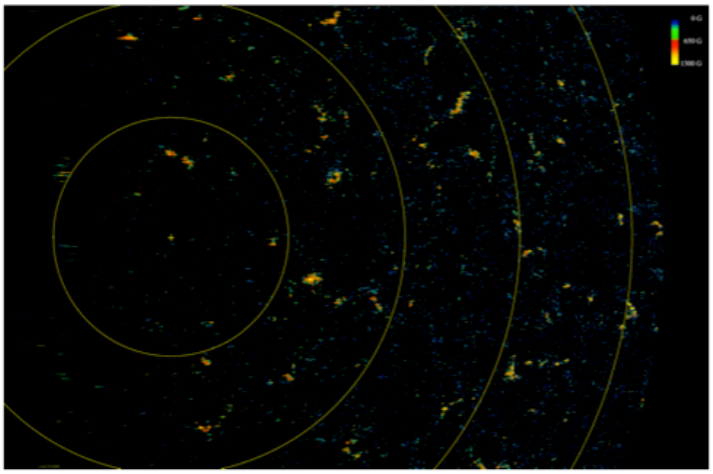
The SPI mission defined here will also contribute to important "multi-viewpoint" science objectives and will complement near-Earth remote sensing and *in-situ* measurements (e.g. SDO, Solar Orbiter and Solar Probe Plus). However, we have limited the primary objectives to those that **require** the viewing geometry provided by the SPI orbit. Science objectives that could be addressed by a similarly instrumented spacecraft in a low latitude orbit separated from Earth primarily in longitude only should be considered "bonus" science for the SPI mission.

Figure 2 Solar rotation rate ($\Omega/2\pi$ nHz) versus depth (solar surface is at 1.0). The white polar and deep regions where the rotation rate is currently unknown will be filled in using SPI (Based on Schou 1998).



The primary goal of SPI is to provide local and full-Sun helioseismology and to characterize the behavior of the solar magnetic field at the poles and its evolution with the solar cycle. Knowledge of the high-latitude convection, meridional circulation and differential rotation is crucial for understanding magnetic flux transport, polar field reversals, the solar dynamo, solar cycle

Figure 3 Hinode observations of solar landscape showing presence of strong horizontal and vertical magnetic fields (0 G is Blue; 1300 G is Yellow)



models and predictions. Understanding these flows will significantly further our understanding of the solar dynamo. Doppler data from the Michelson-Doppler-Imager (MDI) on SOHO and the ground-based Global Oscillation Network Group (GONG) have revolutionized our views of the structure and dynamics of the convective region and the solar dynamo. Figure 2 shows measurements of the differential rotation as a function of depth from SOHO/MDI data. A region of large velocity shear can be seen at about 0.7 R_{Sun}; it is this shear, at the base of the convection zone (tachocline) that is now thought to drive the large-scale solar dynamo. Observations from the Solar Optical Telescope on Hinode during the periods of the highest inclination of the solar axis to the ecliptic have shown that the polar regions are populated by small-scale kilogauss magnetic fields (see Figure 3 from Tsuneta et al, 2008) and that supergranulation forms curious alignment patterns in the near-polar regions (Nagashima et al, 2010). However, the Hinode observations gave us only a glimpse of the structure and dynamics of the near-polar region. Missing are systematic measurements of the flows and magnetic fields in the polar regions. The current ecliptic-viewpoint observations do not provide measurements of sufficient accuracy for helioseismic inversion of the solar structure and rotation in the polar regions. In addition, SPI will enable measurements of the deep interior using a new technique called stereoscopic helioseismology based on time–distance helioseismology. This technique uses observations from helioseismic instruments placed at least 120° from each other: one aboard SPI and one ground-based instrument such as GONG, or space-based instrument such as HMI aboard SDO. The observation of the propagation of waves in the core of the Sun from both sides will enable to recover the structure of the deep convection zone, tachocline and the energy-generating core.

The high-latitude viewing will provide a unique opportunity to study the dynamics of meridional flows and rotation in the polar regions and search for deep longitudinal structures in the tachocline. Figure 4 shows the sound wave ray paths (dashed lines) that will enable us to measure the subsurface meridional flows (solid lines) using SPI's high latitude viewpoints. Long periods of nearly continuous high latitude (above |60°|) viewing of the polar regions are required for determination of the meridional flows, supergranulation, and their rapid changes (on the scale of days) in the polar regions using local techniques. This is because these large-scale flow patterns have small velocities compared to the fluctuating velocities of the turbulent convective zone, and thus long periods are need to average over the fluctuations to determine the mean flows. Uninterrupted polar region observations lasting at least 8-24 hours are required for determination of the surface and sub-surface flows; determination of the polar flows throughout the convection zone down to the tachocline (depth 200 Mm) requires long (many day) continuous observations of the polar regions. ***This is the driving requirement for defining a mission with an orbit inclination of 75°, replacing the 60° inclination recommended in the 2003 SEC Roadmap study.*** An orbit with 60° inclination would allow determination of the flows in the polar regions in the upper convection zone, but not down to the bottom of the convection zone. For the SPI science orbit, the spacecraft is at high latitude (more than |60°|) for 29% of the time. The orbit provides 36 days at >35° latitude, 28 days continuous viewing of >45°, and 17 days at >60°.

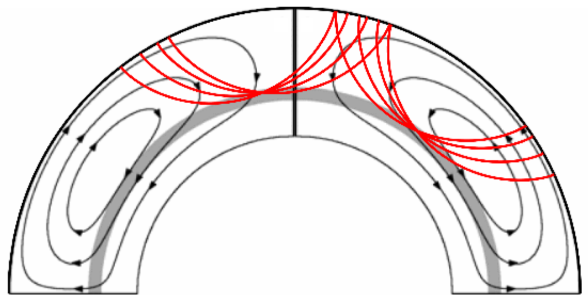


Figure 4 Closed circulation lines: Possible streamlines of meridional flow. Red lines: Sound wave (p-mode) ray paths that can be used to measure the subsurface meridional flows using SPI's high latitude.

Along with the Dopplergrams, magnetograms will be taken every 5 minutes to observe the response of the magnetic field to the surface, sub-surface and interior flows. Together, these observations will be used to study phenomena such as the evolution of active regions, flux transport and the solar cycle field reversal. SPI, complemented by near-Earth magnetograph observations, will enable us to follow the evolution of active regions for much longer than the half-solar rotation now possible. With only observations from Earth, each longitude and latitude is visible 50% of the time; with observations from both Earth and SPI, this increases to nearly 80% for all longitudes and latitudes. This allows improved studies of the evolution of active regions in response to the flows determined by helioseismology as well as to improved multi-viewpoint "synoptic" magnetograms.

Another key aspect of understanding solar variability is the ability to link variations in the heliosphere to solar surface conditions. *In-situ* measurements of the solar wind plasma, the heliospheric magnetic field, energetic particles and isotopic and elemental composition are required to fully address this issue. The high latitude operations, rapid latitude scans (~4 months) at fixed radius, and the low solar distance of the SPI orbit allows the study of the evolution of the solar wind from its source to the spacecraft nearly free of the effects of stream-stream interactions. This, along with improved magnetic field extrapolations using the multi-viewpoint synoptic magnetograms, provides an unprecedented opportunity to determine the source regions of the solar wind.

The polar perspective of SPI has distinct advantages for space weather prediction. STEREO has shown the advantage of a second viewpoint for predicting the arrival time of Earth-directed CMEs. The SPI coronagraph will be able to observe Earth-directed CMEs from the high-latitude perspective. For events that are "halos" as viewed from Earth, this will give far better speed estimates so that even the very fast CMEs, which are closely associated with the largest and most hazardous solar energetic particle events, can be tracked.

A concrete manifestation of the short-term variability of the Sun is the production of energetic particles that can reach several hundred MeV/nucleon. At 0.48 AU the velocity dispersion effects are greatly reduced and the magnetic field lines can be more readily traced back to the source regions on the Sun. This makes it possible to relate flare-accelerated particles to their sources and to identify the time and altitude at which CME-driven shock acceleration begins near the Sun with much greater precision. The fast latitude scans of the SPI orbit permit frequent snapshots of the latitudinal gradients in the intensity of anomalous and galactic cosmic rays which can be used to determine the diffusion coefficients for particle transport both parallel and perpendicular to the magnetic field. Measurements from ACE and the two STEREO spacecraft at large longitudinal separations show that the energetic particles accelerated in solar flare events rapidly spread over a broad range of heliolongitudes, contrary to expectations for a point-like release of particles. The longitudinal transport mechanism remains to be established. SPI will be able to determine how energetic particles are transported in latitude and allow the study of how coronal hole boundaries influence particle transport.

Measurements of the variation of the total solar irradiance (TSI) is fundamental to our understanding both the Sun-Earth Connection and the Sun as a star. The SPI orbit is ideal for determining the latitudinal variation in TSI; the rapid changes in solar latitude enable a complete 360º sweep every 4 months with polar and equatorial observations separated by only ~30 days. Through comparisons of the high latitude observations with simultaneous in-ecliptic observations from instruments on other platforms, a true measure of the latitudinal variation of TSI can be determined. With parallel modeling efforts, polar brightness contributions and those caused by magnetic activity could be better characterized. Moreover, measurements of the TSI from the different perspectives provided by SPI will help with the interpretation of observations of sun-like stars whose rotation axis orientations must be deduced. This should help to decide the still open question as to whether the Sun's brightness variations are substantially lower than other Sun-like stars.

4. Instrument payload

To meet the science goals of the SPI mission an instrument package has been designed to optimize the science return while economizing in mass, power and cost. Table 1 summarizes the instrument suite on board SPI. The coronagraph pointing control is driven by the inner field of view cutoff. The pointing knowledge for the EUV Imager is determined by pointing control requirement of the coronagraph while the EUV Imager pointing stability assumes 2.5 arcs pixels and a 1024×1024 CCD with exposure times from 15s to 30s and jitter amplitude <1 pixel. The power requirements are upper limits. Power savings of almost a factor of 10 will be possible by replaceing the CCD detectors with CMOS Active Pixel Sensors

Table 1. Instrument Payload

	Remote Sensing Instrument Package					*In-situ Instrument Package*		
	Doppler Magneto-graph	**Coronagraph**	**EUV Imager**	**TSI Monitor**	**UV Spectrograph**	**Magneto-meter**	**Solar Wind Ion Composition & Electron Spectrometer**	**Energetic Particles (20 keV/nuc – 100 MeV/nuc)**
Mass (kg)	5	8.25	7.6	7	6	1.5	4	4
Average Power (W)	4	10.4 for both Cor & EUV		10	6	2	6.5	3.1
Pointing Control (3σ)	0.5°	0.1°	0.5°	0.5°	30″	0	2°	n/a
Pointing Knowledge (3 σ)	0.5°	0.1°	0.5°	0.1°	15″	0.1°	0.5°	2°
Pointing Stability	0.2” in 10s (3σ)	7-10 arc-s/s (3σ)	1.5 arc-s for 4s (3σ)	0.1°/s (3σ)	0	0	0.1°/s	n/a
Avg. Data Rate (kbps)	75	41	41	0.3	10	0.6	0.2	0.5
Field of View	1.5°x1.5°	8° half-angle 1.5-15 R_s	2.5° half-angle	2.5°	10″ x 1.4° (instantaneous FOV of slit)	n/a	Ion sensor: 10°x90° Sunward e^-: 20°x90° Backward e^-: 20°x160°	LEPT: 120°x20° SIT: 20°x20° SEP: 45° cone

currently developed for Solar Orbiter.

The helioseismology science objectives discussed briefly above require an instrument capable of producing Doppler images as well as line-of-sight magnetograms. The baseline instrument considered consists of conventional polarization analyzers and a magneto-optical filter (MOF) type of optical resonance filter. The MOF-based DIMAG design has been successfully employed in ground-based applications and extensively studied for spaceflight applications. The combination of intrinsic stability and imaging capability allows the MOF based instrument to address a wide range of science objectives, with an optimal use of on-board resources.

The magnetic field and helioseismology studies are augmented by a range of imaging observations designed to provide both coupled and stand-alone science. The combination of a coronagraph, a EUV Imager, and a UV spectrograph will provide new insight on the evolution of active regions and their response to the magnetic field as well as allowing us to determine the global 3D structure of the corona and inner heliosphere. In addition, the coronal imaging instruments will yield new observations on the global effect of CMEs on the large-scale corona and help determine the physical characteristics of the source regions of CMEs and Solar Energetic Particles. The coronagraph and EUV Imager instruments are based on heritage from SECCHI coronagraphs and SOHO/EIT, respectively.

The particle characteristics of the solar wind and those resulting transient events are observed by the *in-situ* instrument suite which will enable us to sample the solar wind closer to the Sun and in high latitude regions where the interplanetary field is less wound by solar rotation. To meet the energetic particle objectives it is necessary to measure protons, helium, and heavy-ion composition from C to Fe over a wide energy range. It is also necessary to measure solar electrons, to separate ^{3}He and ^{4}He, and to distinguish sunward and anti-sunward particle flows. These measurements can be accomplished with several small telescopes of standard design, such as those on STEREO. The energetic particle package is based on heritage from LET, HET and SIT instruments on STEREO which have broad coverage, include new low-mass, low-power designs, and were designed for a 3-axis stabilized spacecraft.

A differential electrical substitution radiometer will provide a state-of-the-art TSI measurement at all available solar latitudes. Such an instrument measures the difference in compensating electrical power required to maintain a constant temperature in two cavities: one exposed to the Sun through a known aperture and another, reference cavity having no solar exposure. An example of such a design is the Differentially Balanced Solar Irradiance Monitor (DBSIM), under development at NASA/JPL.

5. Conclusion

The Solar Polar Imager mission uses solar sail propulsion to place a spacecraft in a 0.48 AU circular orbit around the Sun with an inclination of 75º. Observations from such a vantage will revolutionize our understanding of the internal structure and dynamics of the Sun and its atmosphere. The rapid 4 month polar orbit combined with a suite of *in situ* and remote sensing instrumentation further enables unprecedented studies of the physical connection between the Sun, the solar wind, and solar energetic particles. By providing a unique perspective on the global structure and evolution of the Sun and its corona, the SPI will significantly advance our knowledge of key solar phenomena, our understanding of the Sun as a star, and our forecasting abilities for the Sun's effects on the space environment. The observations of the polar region are at the heart of understanding one of the fundamental questions in solar physics and astrophysics: how and why does the Sun vary?

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White Paper for the NRC Decadal Survey for Solar and Space Physics

Research-to-Operation of Predicting Neutral Density

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Abstract

Significant improvements in research-to-operation of predicting satellite drag will come from the use of physics-based atmospheric density models. This will lead to a near-real-time, accurate operational capability to estimate future locations of satellites with high accuracy.

Orbital aerodynamic drag continues to be the largest uncertainty in determining trajectories of satellites operating in Earth's upper atmosphere below about 600 km. Neutral density of the upper atmosphere (thermosphere) is the major uncertainly in determining satellite drag. Winds are significant particularly during geomagnetic storms. Therefore understanding and forecasting the global density and wind fields permits accurate satellite drag forecasts. Many manned and unmanned space missions operating in Low Earth Orbit require forecasts of satellite drag. One major thermospheric variability societal impact is the space debris threat to these missions. Air Force Space Command (AFSPC) has responsibility for providing Collision Avoidance Warnings for all satellites. Their goal is 72 hour drag forecasts within 5%. AFSPC needs upgraded operational assimilative satellite drag space weather for precise knowledge of locations of all satellites and predicting where reentry will occur. Current AFSPC forecasts during unstable orbital drag environment conditions may be in error by as much as 50%.

Since the thermosphere is driven by solar EUV and solar wind inputs as well as upward propagating disturbances these are the parameters that must be forecast. The major space weather challenge is forecasting the spatial and temporal response to geomagnetic storms. Large geomagnetic storms produce large disturbances in the upper atmosphere with wind speeds as high as 1 km/s. In addition, Solar EUV activity is currently near its minimum but is expected to reach maximum values in 2013. During solar max, orbital predictions are far less accurate and the risk of collisions increases significantly; more objects tend to deviate from their expected paths and more reenter. While solar cycle effects dominate on longer time scales, a strong space storm can typically change the neutral density at 400 km by a factor of 3 in just a few hours.

Current state of art density models are semi-empirical representations of the atmosphere and are based in part upon proxy of solar and geomagnetic heating inputs. These empirical models can adequately describe the neutral density global mean structure within 15-20% during quiet times. However, errors of 100% are not unusual during disturbed periods. A significant advance in specification of satellite drag was achieved by The Air Force High Accuracy Satellite Drag Model (HASDM) . This approach assimilates drag data from some 100 calibration satellites to correct the global density fields of an empirical model to reduce errors to about 4-8%. Due to coverage issues, accuracy at high latitudes is more limited, particularly during geomagnetic storms. Further, given its temporal and spatial resolution it will provide only limited accuracy during geomagnetic storms even with timely forecasts of appropriate indices.

Significant improvements beyond this state will come from the use of physics-based atmospheric density models in place of the current semi-empirical models. Considerable RDT&E is required from the space physics and astrodynamics communities for this advancement to occur. Additional capabilities to understand and forecast the satellite drag dependence on the space weather environment are coming from new solar and geomagnetic observations plus the large direct satellite-borne density data sampling of the atmosphere vs latitude, local time, day of year, solar cycle and geomagnetic activity from the CHAMP and GRACE satellites and orbital drag databases generated by AFSPC. The satellite drag prediction accuracy, especially over a 72 hour prediction period, is found to be mainly a function of the predicted accuracy of the solar and geomagnetic indices coupled with the accuracy of the atmospheric model using these predicted indices. Physics-based models offer an advantage by providing realistic heating inputs and detailed, time-dependent structure not available in the semi-empirical models. Knowledge of the required fundamental heating processes resulting from the EUV and solar wind interaction with the coupled magnetosphere–ionosphere-thermosphere system are in an active research state.

The Multidisciplinary University Research Initiative (MURI) with the University of Colorado (Dr. Jeff Forbes, PI) was created by Air Force Office of Scientific Research (AFOSR) to explore the physical mechanisms that drive the Earth's thermospheric dynamics. Candidate physical modeling tools are available including the physics-based neutral density model called the Coupled Thermosphere-Ionosphere Model (CTIM). Considerable research has contributed to development of NCAR's Thermosphere-Ionosphere Electrodynamics General Circulation Model (TIEGCM). The MURI program attempts to address current model limitations through scientific analyses of solar phenomena and available satellite drag data. The scope of this MURI topic is not the development of a new physics-based model but "the elucidation of those physical concepts and predictable key indicators of energy inputs to the atmosphere that will update and calibrate current operational satellite drag models and lead to the accurate prediction of thermospheric densities and, hence, a precise prediction of the locations of satellites. …. The intent of this MURI is to develop fundamental concepts that will eventually be included in the large models." The MURI effort has been divided into seven focus areas including Forecasting Geomagnetic Activity, Forecasting Solar EUV/UV Radiation and Wave Forcing from the Lower Atmosphere. A variety of solar disturbance and solar wind propagation models are applied to this research. In addition to developing forecast tools the MURI effort is investigating the response of the thermosphere to heating inputs and, with the Whole Atmosphere Model (WM), to investigate upward propagating waves.

The fundamental next step after the MURI is to incorporate the benefits of a physical model within the assimilation process. Initializing the physical model with both direct in-situ and indirect observations in a statistically rigorous manner provides a practical approach for representing the time-dependent conditions of the thermosphere. Implementation of a Kalman filtering data assimilation technique by the space physics community has proven to be non-trivial. It requires detailed understanding of the physics based model as well as estimation theory and astrodynamics. Thus, this development requires cooperative efforts of the space physics and astrodynamics communities. Employing physics-based neutral density models coupled with an assimilation technique should be the basis of next-generation drag model improvements for satellite cataloging.

In summary, uncertainties in neutral density variations have been the major error source for LEO determination. The problem is being vigorously and fruitfully attacked by numerous space weather studies including data assimilation schemes, predictive solar indices, and in-situ measurement. While there is still a lot of research needed, the tools are finally becoming available. The culmination of these efforts will be steady progress in meeting the evolving, previously unattainable, stringent requirements for operations in the satellite drag environment. A key research goal of the AFOSR MURI is a physics-based understanding and prediction capability for the spatial and temporal distribution of thermospheric energy sources. This critical basic research will lead to a near-real-time, accurate operational capability to locate, track identify, and estimate future locations of satellites with high accuracy. With the additional underpinning of this effort, we anticipate significant future progress in satellite drag capability.

White Paper on: **Expansion of the Heliophysics Explorer Program**

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Abstract: The Explorer missions for Heliophysics have an unbroken record of tremendous science accomplishments, the most innovative implementation, by far the best science return per dollar, the fastest development from selection to launch, the best schedule compliance, the best-controlled costs from proposal to end of life, and very long productive lifetimes. In all aspects, Heliophysics Explorers represent an ideal that all NASA missions aspire to achieve. We propose that the Heliophysics community should expand this outstandingly successful program as much as possible, to maximize the science for the Heliophysics dollars. We recommend: 1) the rate of Heliophysics Explorers be increased immediately to at least one per year, alternating between SMEX and MIDEX; 2) MIDEX be expanded in cost (and science scope) to allow use of presently available low end Atlas/ Delta launch vehicles; 3) a third category of Mini-Explorer (MINEX) be established with a cost cap of ~$50 million (TBD) that could cover micro-spacecraft, Ultra-Long Duration Balloon (ULDB) missions, etc; 4) the Explorer Missions of Opportunity (MoOs) should be continued and expanded, if possible. We also recommend strong, stable funding for Heliophysics Suborbital and Instrument Development programs since that's where much of the best new technology for Explorers originates.

The Explorer program is the shining star of the field of Heliophysics. Each of the six Small Explorers (SMEX) – SAMPEX, FAST, TRACE, RHESSI, THEMIS, AIM, IBEX – and two Middle-class Explorers (MIDEX) - IMAGE, THEMIS - have opened up new areas with new technology instruments and/or new innovative implementation. Each has been developed from selection to launch very rapidly, the fastest of any class of space mission, and with costs close to those proposed; the infrequent delays and small overruns have invariably been due to circumstances beyond the mission's control – especially launch vehicle delays or NASA policy changes. Each has been productive for much longer than its prime mission duration, thus producing far more great science than proposed; and usually stopping only because funding drops below that required for operation. The Heliophysics Explorer program performance is nearly perfect compared to any other NASA program.

What might be the reasons for this success?

1) Competition - The Explorer program is extremely competitive; to be selected a mission has to be near perfect in every respect – compelling science (usually requires innovative instrumentation/implementation), technical readiness, implementation, management, cost. This forces the proposer to not only have

compelling science, but with a well-developed instrument(s), with strong management, and well-known costs. One might logically argue that larger programs should be similarly competed.

2) Principal Investigator led - The missions are led by a single Principal Investigator, a scientist, whose own future is tied to the scientific success of the mission. He (or she) has the power to structure the management (must be such as to be selectable), make the key trades and decisions about descopes, etc., with little interference from NASA (although sometimes NASA changes these rules - e.g., following the two Mars failures).

3) Experience - Scientists in the Heliophysics community, unlike the Earth Sciences, Planetary, and most of Astrophysics, has long had a tradition of developing their own instruments for rockets, balloons, and eventually space missions.

4) Support - The excellent support (without undue interference) of the Explorer office at NASA Goddard Space Flight Center.

5) Cost cap - The proposer knows the cost cap before writing the proposal, and he knows that if his costs are unrealistic he will not be selected. If the mission runs into problems, the PI knows he as to solve them within that cost cap or risk being canceled.

6) Almost all Heliophysics science objectives can be addressed with Explorer missions. Unlike Astrophysics where observatories the size and complexity of Hubble, JWST, Chandra, Compton, Fermi, Spitzer are required for the science, the Heliophysic Great Observatory is best made up of missions of Explorer class or slightly larger. Even when it might seem at first glance that a larger mission is required for the science objective, the community should have the opportunity to directly compete with one or more PI-led Explorers; for Heliophysics it’s likely that except in extremely rare cases, an expanded Explorer will be able accomplish the science.

7) Data policy – most of the Heliophysics Explorer programs have enthusiastically adopted NASA’s policy of open data access. This has greatly amplified community participation and science productivity.

A major risk in the large, non-Explorer class missions is enormous cost growth. For Astrophysics, the JWST cost growth has essentially crowded out almost all other science. Expansion of the Astrophysics Explorer program is thus the top priority, except for the WFIRST mission, in the recent Astrophysics Decadal survey, ahead of all other major missions. Heliophysics has also experienced very large cost growth on some large missions from the time of selection. We certainly do not want the same fate happening to us as happened to Astrophysics. Rather, we should try to expand the Explorer program as much as possible without losing its advantages. Thus, we recommend:

1) The rate of Heliophysics Explorers be increased immediately to at least one per year, alternating between SMEX and MIDEX.

This was the goal of the original Explorer program. This mix of SMEX vs MIDEX may be difficult for Astrophysics but certainly suitable for Heliophysics.

2) MIDEX be expanded in cost (and science scope) to allow use of presently available low end Atlas/ Delta launch vehicles.

The loss of the Delta 2 launcher has stopped the MIDEX program. The solution is to allow MiDEX to utilize the currently available low end Atlas and Delta launch vehicles, and expand the cost-cap and scope for MIDEX. We note that Planetary Discovery and Mars Scout missions use those vehicles but are PI-led like Explorers, even though the cost cap is much higher. Because Heliophysics scientists have the instrument/mission experience that Planetary scientists lack, it's likely that Heliophysics will be more successful in mission of that cost level. It also allows the Explorer way of doing business (competed) to be expanded to missions of that cost level.

3) Start a third category of Mini-Explorer (MINEX) with a cost cap of ~$50 million (TBD) that could cover micro-spacecraft, Ultra-Long Duration Balloon (ULDB) missions, etc.

This is expanding the Explorer way of doing business to smaller, but scientifically exciting missions that use novel platforms, both big and small. Some science areas (e.g., cosmic rays) require enormous payloads and long observing times. On the other hand, technology developments have opened the door to miniaturized instruments that can be flown on micro- or nano-satellites.

4) Continue (and expand, if possible) the Explorer Missions of Opportunity (MoOs) that have been so cost-effective.

In addition, most, if not all, of the Heliophysics Explorers utilize new breakthrough technology that was developed through the Suborbital program and the Instrument Development program. An additional recommendation is that these programs need to have robust stable funding.

Next Generation Space Science with the Geospace Array

Frank D. Lind
MIT Haystack Observatory

1.0 Introduction

The Geospace Array is a next generation digital radio array capable of active and passive measurement of the Geospace environment. The system would be deployed globally to provide ground based measurement of fundamental physical parameters in the Geospace environment. The system will address science topics from the lower atmosphere to the surface of the Sun and the larger universe beyond. The application of the instrument to these diverse areas and support of a large scientific user base are enabled by the flexibility of the Array's technical approach and the all digital software radio technology which will be used to implement the system. In many areas the Geospace Array will provide major advances in resolution, measurement speed, coverage, occupancy, consistency, and responsiveness over existing ground based radar instruments. The Array will enable significant advances in our physical understanding of the atmosphere, the space environment, the Sun, and the coupling between them by allowing physical measurements of the critical regions which can then be studied in a system science context.

The core goals of the Geospace Array project are as follows :

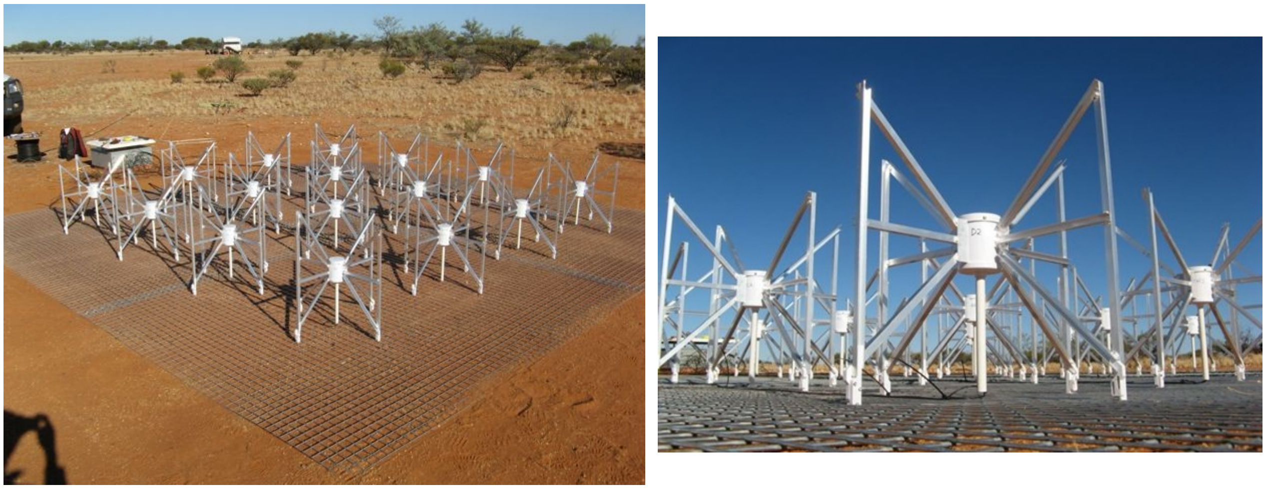
- Address Upper Atmosphere science topics of wide importance
  - Image the global dynamics of geomagnetic disturbances and storms
  - Monitor the coupling of energy and momentum in the upper atmosphere
  - Explore the plasma physics of ionospheric layers, irregularities, and instabilities
- Address Lower Atmosphere science topics using a wide range of radar capabilities
  - Image the atmospheric boundary layer over wide volumes
  - Observe the coupling of energy from the lower to the upper atmosphere
- Allow for broad and simultaneous application to Heliospheric science topics
  - Coronal mass ejection tracking in the heliosphere via interplanetary scintillation
  - Exploration of transient Solar events over wide extents in frequency with high sensitivity
- Provide the next quantum leap in capability compared to existing radar systems
  - High power-aperture with broadband operation (VHF, UHF, L-band, S-band)
  - Fully digital element technology with wide receive bandwidths (500 MHz to 1 GHz)
  - Simultaneous transmission and reception on separated bands
  - Volume imaging of atmospheric regions at high resolution for coherent targets
  - Large numbers of simultaneous, adaptive, and independent receive beams (1000s)
  - Software Radar Supercomputing for signal processing and analysis
- Fully automated, always on, and on demand operations at a sustainable cost
  - Web based remote operations, control, visualization, and experiment design
  - Simultaneous realtime application of the instrument to multiple experiments
  - Adaptive experiment execution in response to observed conditions
- Address a wide range of national needs beyond scientific inquiry
  - NASA - Space mission ground based science support
  - DoD - Air Force (Space Situational Awareness)
  - NOAA - Space Weather monitoring
- Provide a sound basis for diverse and wide reaching community involvement
  - Education through direct instrument access and realtime classroom interaction
  - New science capability development directly by the community
- Provide a clear path for the long term evolution and growth of facility capabilities
  - Software defined instrument capabilities and analysis - growth through new techniques
  - Scalable in aperture, extent, burst capture capability, and computational power

The Geospace Array is a next generation ground based radio and radar observatory network which would succeed the existing NSF ground based upper atmosphere facilities for providing fundamental and sustained measurement of the Geospace environment. The Array would apply radio and radar techniques of well demonstrated capability to enable measurements from the lower atmosphere, into the ionosphere, through the heliosphere, and to the surface of the Sun. The all digital and computing-focused technology used to implement the Array will create a consistent approach for addressing a diverse range of scientific topics. Measurement techniques will be implemented as software running on high performance computing systems. It will be possible to use the Array to perform multiple science experiments simultaneously. The software radio technology used to implement the Geospace Array will be very flexible in its application.

The Geospace Array will be a globally deployed hybrid of a digital array radar and a digital array radio-telescope. The Array system will use a large number of broadband radio receivers and separate narrow band transmitters which will be distributed in a series of moderate power-aperture tiles. Different transmit frequency bands will be implemented using tiles designed for specific frequency ranges to limit system complexity and to allow tradeoffs in total emitting power as a function of frequency. At a given site these tiles will be arranged using an aperiodic geometry with separations up to several tens of kilometers to obtain appropriate array performance for radar and radio imaging over a significant portion of the full sky. A lower density of tiles would also be distributed between sites at appropriate locations to provide additional multi-static observation capabilities. The majority of the tiles at a major site would be deployed in a dense central core to enable sufficient aperture for incoherent scatter radar measurements of the ionosphere. The exact number of sites, elements, and tiles would be determined by a formal design study. Conceptually an array capable of global monitoring might consist of on the order of several million elements deployed in on the order of 20 to 30 major sites. This would enable a series of major deployment sites which would provide coverage for the major regions of Geospace (i.e. the Sun, Heliosphere, Auroral zone, sub-auroral, mid-latitudes, anomaly regions, and magnetic equator). Figure 1 shows existing incoherent scatter radar facilities which currently provide a subset of the capabilities which would be enabled by construction of the Geospace Array.

Figure 1 : Existing incoherent scatter class radar facilities in the world are a precursor of the Geospace Array.

Figure 2 : A tile and closeup of the Murchinson Widefield Array (a digital radio telescope in Western Australia). The Geospace Array tiles would be conceptually similar, somewhat more robust, and use aperiodic geometries.



Individual tiles would be constructed to provide good visibility over the whole sky and several different physical configurations to achieve this would be considered. Figure 2 shows a photograph of a Murchison Widefield Array (MWA) tile and Figure 3 shows the conceptual layout of the MWA deployment. This MWA design is conceptually similar to the tiles which would compose the Geospace Array. The tiles could be made more robust individually but the lack of physical infrastructure (e.g. platforms, buildings, etc.) is important for minimizing system cost. Data would be transported over fiber optics to computing facilities for real-time processing, analysis, and incorporation in assimilative models. These computing facilities would include access to centralized national computing centers where appropriate for the analysis of critical Space Weather events.

The all digital Array elements would interleave operating modes on a fine scale (milliseconds) and would couple directly into a software radar architecture [Grydeland et al. 2005] to provide the computing power for application of the array to a wide range of simultaneous scientific investigations. The use of multicore graphics processor units (GPUs) combined with high speed networking capability (10 to 100 Gbit) would enable the application of map-reduce architectures to ensure highly parallel and scalable processing of signals. Next generation GPU units are expected to provide more than 10 Tflops per chip which will allow the signal processing requirements of the

Figure 3 : Conceptual layout of the MWA deployment. The Geospace Array would use similar aperiodic tile layouts at major sites. Each red dot represents a tile and black lines represent network connections.

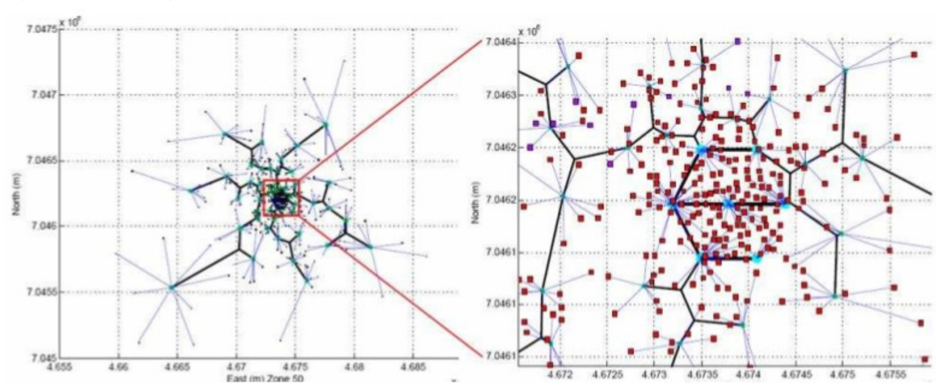
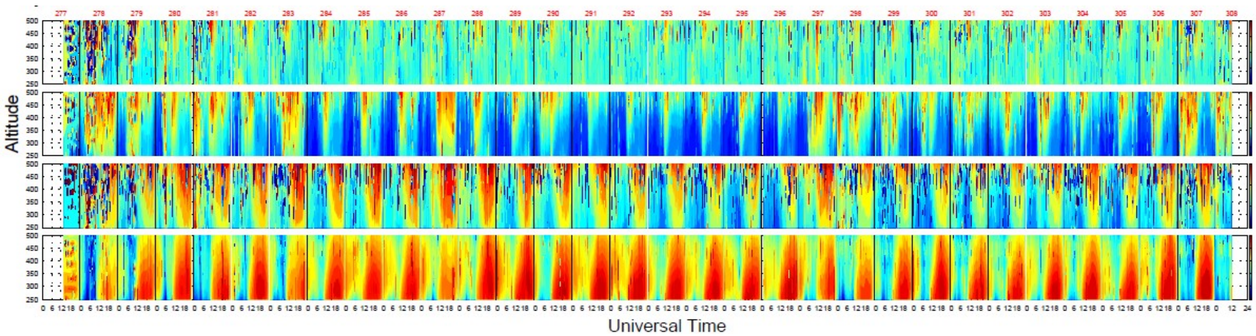


Figure 4 : Incoherent Scatter radar measurements of the ionosphere over a one month period from MIT Haystack Observatory's Millstone Hill UHF Radar [Zhang et al., 2005]. From top to bottom the parameters shown are line of sight velocity (m/s), electron temperature (K), ion temperature (K), and electron density (log Ne) as a function of time and altitude over 30 days.



Geospace Array to be achieved. The all digital implementation offers great flexibility compared to existing instruments and enables the addition of new measurement and analysis capabilities purely as software implementations.

2.0 Upper Atmosphere Science

The Geospace Array will provide a unique capability for addressing important physical processes and Space Weather effects in the Upper Atmosphere and near space environment in a system science context. The range and significance of processes visible to the Geospace Array will include all regions of the ionosphere and the boundary layers between them. These regions are coupled to the magnetosphere and heliosphere by the Earth's magnetic field and interactions at the boundary layers such as in the Auroral zone, the plasmasphere boundary layer, and the Earth's ring current. In particular an ability to observe the ionosphere over a wide range of altitudes and latitudes in a continuous and flexible manner is critical to a quantitative and experimental understanding of the Geospace environment and Space Weather forecasting.

To enable this measurement capability a major focus of the Array's design will be to enable use of the incoherent scatter radar technique [Farley, 1961; Evans 1969] on a large scale. An example of incoherent scatter radar data is shown in Figure 4. This technique is unique in its ability to make spatially resolved measurements of many fundamental plasma parameters (i.e. electron density, electron temperature, ion temperature, plasma velocity, plasma composition) as well as a large range of derived parameters over wide spatial regions and altitude ranges. The Array will also provide unprecedented performance for coherent scatter observations and three dimensional radar imaging of ionospheric irregularities which have been widely important [Foster and Erickson, 2000 ; Makela 2006] for detecting and understanding plasma instabilities and their role in the Geospace system.

Understanding the dynamics of Geospace phenomena requires rapid measurement capabilities, the ability to follow phenomena in motion over the full sky, and the ability to resolve three dimensional structures rapidly. The Geospace Array will resolve both large and small physical scales and give access to the meso-scale picture as well as the micro-scale dynamics on an continuous and ongoing basis. Such dynamic pictures are of particular importance to our understanding of coupling in the Geospace environment (e.g. [Foster et al. 2002]).

The Array will be a ground based Space Weather radar network which enables monitoring, study, and prediction of the Geospace environment in a sustained and cost effective manner. It will also provide the central physical measurement capabilities necessary to understand the regional observations made with growing networks of distributed instrumentation. Such Distributed Arrays of Small Instruments (DASI) have been called out by the National Research Council [NRC, 2006] as a major potential growth direction for space science research. The Geospace Array is not itself a small instrument but it has a strong relationship to the concepts associated with the overall DASI effort.

3.0 Lower Atmosphere Science

The Mesosphere-Stratosphere-Troposphere (MST) region has a rich variety of winds, tides, waves, and turbulence that can be observed using ground based radar techniques [Balsley and Gage, 1980]. Scientific investigations over this wide altitude regime are by nature very cross disciplinary and will be addressed well by the Array's multi-role capabilities. Understanding the sources, energetics, and scale sizes of energy coupling from the lower atmosphere to the upper atmosphere, along with resulting ionospheric effects, is critical to a detailed knowledge of overall upper atmospheric energy balance. Upward energy flow from the stratosphere, to mesosphere, and thermosphere is of major importance to the NSF CEDAR community. Current community critical science topics in this area include studies of lower atmospheric tidal variability and its interactions with mean atmospheric circulation, gravity waves, planetary waves, and ionospheric variations [e.g. Immel et al 2006], gravity wave excitation mechanisms [Fritts and Alexander, 2003], and the implications of significant observed gravity wave geographical and temporal variability [Allen and Vincent, 1995]. Geospace Array measurement capabilities will allow contributions in all these areas and their relation to upper atmosphere phenomena.

The Array sites will be able to image the atmospheric boundary layer using techniques similar to those of other MST radar systems [Gossard, 1990]. Such imaging approaches provide insight into three dimensional flows and structure in a manner free of time-space ambiguities [Mead et al. 2007 ; Chilson 2004; Chau 2000]. The Array will also be able to observe clear air turbulence using multiple radar wavelengths [Cohn, 1994]. Three dimensional volume imaging capabilities of velocity fields over wide spatial extents and over a range of wavelengths will furthermore provide a strong separation of time and space variability and will lead to insights into energy coupling and dissipation in convective systems. Study of microphysical structures associated with larger mesoscale systems is also possible [e.g. Palmer et al. 2005]. Combined with the system's thermosphere and ionosphere measurement capabilities, the Geospace Array will be a uniquely capable instrument for the monitoring and study of lower atmosphere/upper atmosphere energy coupling.

4.0 Heliospheric Science and Radio Astronomy

Knowledge of the Sun and the heliosphere has great general importance to an understanding of Space Weather in the solar system and as a driver for a detailed understanding of the ionosphere and atmosphere. Understanding the vast intervening region between the solar corona and Earth is crucial to improving our understanding of the solar wind, the interaction of the solar wind with the terrestrial ionosphere and magnetosphere, and to enabling robust Space Weather predictions. The Interplanetary Scintillation (IPS) technique [Hewish et. al, 1964] and heliospheric tomography [Hick and Jackson, 2001] would be applicable directly using Geospace Array to enable the contribution of a large number of IPS measurements to global monitoring efforts. The Geospace Array will also have useful capability for IPS monitoring with a uniquely broadband architecture and a significant burst capture capability. Deep buffering of full sky data will allow intensive analysis of solar radio bursts, coronal mass ejection events, and a wide range of astronomical radio transients. The Array would also be capable of radio imaging of the Solar disk with high resolution on an ongoing basis.

5.0 Facility Use, Education, Community Involvement, and Support

It is expected that implementation of the Geospace Array would result in a widely useful facility with a much greater user base than the existing NSF upper atmosphere radar facilities. Facility operations would transition from the current IS radar operational levels (~20,000 total hours per year) to on the order of several hundred thousand (or more) active beam hours. Dynamic subdivision of array transmission power would enable higher numbers of active beam hours for many modes of operation. The capability of digital generation and analysis of thousands of receive beams would also enable a very high level of instrument occupancy for passive observing applications. Total receive beam-hours by the Array could easily exceed one million per year with the application of sufficient computing power for signal processing and data analysis.

The Geospace Array facility would also enable significant contributions to education. Graduate students would implement new capabilities as software and analytical infrastructure running on the Array and use the data to undertake fundamental investigations to advance our knowledge of the atmosphere, space environment, and wider universe. Undergraduate research projects, through ongoing programs such as the NSF research experiences for undergraduates (REU) effort, would have direct access to the system and would benefit from wide faculty involvement due to the range of scientific disciplines which the Geospace Array would address. Secondary education and public outreach would occur through the existing NSF research experiences for teachers (RET) program and from the ability of graduate, undergraduate, and secondary school educators to obtain direct access to the Array in real time for use in classroom activities.

6.0 Estimated Construction, Operations, and Maintenance Costs

Construction costs for the Geospace Array would be speculative without a specific array design, production ready elements, and quotations at an actual production volume. There are large economies of scale with the production of millions of elements. For a general reference point the MWA per receive element cost is on the on the order of $100 per element in a quantity of less than 10,000 elements. We can imagine that the more capable Geospace Array elements might cost more in similar small volumes but with high levels of integration and mass production the unit costs might approach this level. Implementation of the Array would most likely fall under the NSF Major Research Equipment and Facilities Construction line.

Array operating hours would be strongly divorced from personnel costs as the system would be fully automated and would be operated in an always-on fashion. Maintenance on tiles could occur while the Array was operating without interference or hazard. The greatly simplified operations and maintenance requirements compared to most existing NSF upper atmosphere facilities would allow facility personnel to focus more effort on support of the scientific user community. Operations costs should be comparable to the existing line of NSF Upper Atmosphere Facilities on an ongoing basis.

7.0 Summary

The Geospace Array would provide transformational measurement capabilities in the space sciences through the application of the most advanced active and passive radio-array technology implemented to date on a global scale. The advanced capabilities of the Array are made possible through per-element digital-receiver technology, a hybrid of the radar and synthesis radio-telescope approaches, and a low element power with high aperture design. Technology has now made it feasible to construct this class of instrument at a reasonable cost and operate it in a sustained fashion. This major facility would be directly accessible to many simultaneous users over global data networks.

Application of the Array would address a broad community's needs including diverse scientific interests in the sustained experimental study of the lower atmosphere, ionosphere, heliosphere, and the Sun in a system science context. These are all areas which are directly supportive of major ongoing community and international space science efforts. The Array capabilities are also highly complementary to NASA missions to study the Geospace environment, the Heliosphere, and the Sun. In a larger context the Array would provide global Space Weather capabilities relevant to the national interest for monitoring and characterization of the space environment (e.g. NOAA and DoD). In summary, implementation of the Geospace Array would have broad scientific relevance, wide accessibility, and would be a major milestone in our study of the Geospace environment.

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NRC Decadal Strategy for Solar and Space Physics

Long-term coordinated ground and satellite monitoring of the ring current

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A fundamental measure of the intensity of a magnetic storm is the Dst index, derived from ground-based observatory measurements of the disturbance magnetic field. Dst is often interpreted in terms of magnetospheric ring-current intensity, and as such, it serves as both an important real-time operational diagnostic of changing space weather conditions and as an observational input to theoretical models of the coupled magnetosphere-ionosphere. But because the standard version of Dst is derived from only 4 low-latitude magnetic-observatory stations, and because storm-time ionospheric electric currents also contribute to the disturbance magnetic fields measured at the Earth's surface, there are significant uncertainties in simply interpreting Dst as a proxy measure of ring current intensity. Long-term coordinated ground and satellite monitoring should be able to resolve most of these uncertainties. This would, in turn, facilitate fundamental studies of the physical processes of magnetic storms, and lead to improved space-weather diagnostic measures.

We propose that several existing magnetic observatories operated by foreign national programs be up-graded for real-time data transmission. This work could be coordinated through Intermagnet (www.intermagnet.org), an international consortium that sets standards for observatory operation and promotes the dissemination and usage of observatory data. With 4 or more additional observatories contributing to the calculation of Dst, the accuracy would be improved and, with the resulting improved local-time resolution of magnetic disturbance, the routine monitoring of substorms and partial ring currents could commence. The costs associated with this part of the proposal are very modest: approximately $100,000 per station for up-grades, and approximately $5,000/year for maintenance (which we suggest should be maintained for at least one whole solar cycle). Data feeds would be used by the USGS (geomag.usgs.gov) to support improved Dst services, which would be made available to the general public over the internet.

We also propose that 4 or 8 or more magnetometer satellites be maintained in low-Earth orbits, also for at least one whole solar cycle, and preferably much longer. In order to avoid spatial-temporal aliasing, especially during the high-activity of magnetic storms, we recommend that these satellites be equally spaced in low-ellipticity (circular), low-inclination (equatorial) orbits. This would allow direct comparison of their data with those collected by low-latitude ground-based magnetic observatories, which are also in similar 'orbits'. Polar-orbiting satellites are not always optimally positioned for such studies, and, in any case, their data are complicated by spatial-temporal aliasing, especially during magnetic storms. In this respect, the proposed equatorial satellites would be complementary to polar orbiting satellite networks (such as Ampere). Since both the satellites and observatories would be below the magnetospheric ring current, but with the satellites above the ionosphere and observatories below the ionosphere, a separation of the magnetic signals contributing to ground-based estimates of Dst could be made. The cost for this part of our proposal would need to be worked out, but Cube satellites might be an ideal vehicle; Bob Lin's group at SSL has apparently developed magnetometer Cube satellites with deployable booms. We imagine that it might be necessary to periodically replace the satellites, and, of course, maintenance of real-time data links would also be necessary.

Guest Investigator and Participating Scientist Programs

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SMD's missions are the centerpieces of NASA's science program, and as such deserve the best support possible in order to exploit all the opportunities they offer. However, the challenges of implementing them often results in the expenditure of much of the funding that had been originally set aside for science analysis. Over the last decade, such cost pressures have forced instrument and science teams attached to missions to be extraordinarily lean. Frequently science team members on both the project and instrument sides who participate in mission formulation and implementation, investing time and effort motivated by the science goals they hope to see achieved, find themselves without the support needed to prepare tools and models necessary for interpreting the observations. Fortunately there are a few new projects such as MMS and RBSP that like the past ISTP program, include inter-disciplinary scientists and dedicated theory and modeling teams. This allows both greater community involvement with the mission and enables the projects to make better decisions and plans regarding both mission operations and data acquisition, critical to the magnitude of its success. These teams ultimately form the core of the community mining the mission data. Having had the wherewithal to prepare, the science closure can be evident from the first months of measurements and analysis. As in the ISTP mission, in many of today's missions the involvement of modelers can take full advantage of the arsenal of tools in which NASA Research and Analysis has invested in the years before the mission is launched. Providing such integrated science team opportunities folded into the planning for Heliospheric missions, fosters a sense of mission membership in researchers with desirable skills outside of the instrument teams. The result is more timely and greater science output throughout the project's lifetime.

Another issue is the effect of the long incubation time most missions, especially flagship missions require. Often, by the time data are returned a whole new generation of scientists are on the scene. This younger generation has energy, enthusiasm, new data handling methods, and innovative approaches to old problems. They need a mechanism to become involved in these missions that began years and sometimes decades before. A good solution to this problem is

Guest Investigator (GI) and Participating Scientist (PS) Programs, especially those initiated just prior to launch. These investigators often bring with them unique tools that allow the extraction of key results when the public's, NASA's, and community's interest in a new space probe is at its highest. Post-launch GI and PS programs are additionally valuable because they allow projects to engage those with expertise found to be needed and lacking in the original instrument teams, often in areas where the potential or capability of a data set or instrument was unforeseen or underestimated. Mission instrument teams in general welcome GI and PS participation and are glad to engage these team-unaffiliated participants in their investigations. These programs are a win-win situation for the community, the missions, and NASA who only needs to fund these investigations for the time of their participation.

Heliophysics has maintained a GI program since 2006, with several years of lapse when budgets could not cover them. An examination of the lists of selected proposals available on the NSPIRES website shows a wide spectrum of topics covering missions in all subdisciplines and reaching into the neighboring disciplines such as Sun-as-a-Star and cometary investigations. The list of PIs spans the range of scientist career stages from well-established discipline awardees and NAS members, to mid-career researchers working to establish their own programs, to recent PhDs. The grantees come from Universities, National Labs, NASA Centers, and industry. The GI programs open the mission involvement experience to any qualified applicant.

The desirability and need for scientist engagement in missions in a regular, deeply inclusive way has been demonstrated by decades of mission experience. Programming in adequate support for scientist roles from the mission design phase can make a major difference in the outcome of a mission, including the orbit and operational details, the data obtained, the data products generated, the outside community use of those products, and the efficiency and depth of the science outcome. Especially in these times of increasingly eroded MO&DA funds and the growing list of also desirable extended missions, NASA needs to be proactive in its strategy to get the most out of each mission from its outset. The GI programs and their counterpart PS programs, which are even more closely tied to the mission projects in other disciplines e.g. Planetary, are one way it can maintain this edge and visibly enhance mission success. By this inclusion they can also better fulfill NASA's requirements for training the future technical workforce and expeditiously producing results. Including modeling and theory members in mission teams, together with guest investigator or participating scientist programs wherever possible, will ensure heliospheric physics of a future where its research more effectively influences and benefits the missions we fly.

Extended Missions: Engines of Heliophysics System Science

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While the successful planning, building, launching and commissioning of spacecraft constitutes a remarkable technical feat, the motivation for and end goal of these eyes, ears and hands in space is the science that results from these missions. Level 1 science requirements are developed during the years of formulation and implementation that precede missions. These goals are consistent with those of long-term National Academy Decadal Surveys and NASA Mission Roadmaps that synthesize and prioritize among the many knowledge goals of heliophysics and the other disciplines within the SMD. However, by their very nature, Level 1 Science Requirements are the minimum set that a mission must satisfy in order to achieve its pre-launch objectives, and are dictated in part by budget caps, not simply science objectives. They are focused on what can be achieved during the prime mission, the period of guaranteed operation. They are not the optimal science that can be achieved, nor even the bulk of the science that is ultimately achieved by most missions. In particular, Level 1 Science Requirements cannot cover what can be achieved by extending (or in some cases modifying) the operation of the spacecraft and its instruments, and by combining the observations with those from other spacecraft. Assumptions made about the state of solar activity or other conditions during the prime mission, and even our prior knowledge, may prove incorrect. In addition, unforeseen opportunities can and do arise.

The history of Heliophysics has demonstrated that maintaining the operation of these probes beyond their prime missions invariably provides significant new scientific results and much deeper understanding. A major consideration is their synergistic contributions to the Heliophysics System Observatory (HSO), a complementary multisensor, multipoint study of the heliosphere. The marginal cost of this science is small compared to the cost of the original missions, or of the suite of new missions that would be required to achieve these objectives. A recent example of creative extended mission exploitation is the THEMIS mission’s redirection of two of its satellites to form ARTEMIS, a lunar plasma interaction mission, when it was found that these two spacecraft would have been lost to long eclipses as their original orbits evolved. A recent example of the synergy enabled by extended missions is the use of ACE and Wind particles and fields measurements upstream of the Earth, and SOHO’s enduring work horse LASCO coronagraph, to support the SDO mission. This combination, along with STEREO (in extended mission), also provides a more global heliospheric record of the coronal activity during the intriguing, much-delayed rise of solar cycle 24. Most important, the three imagers combine to give unprecedented complete imaging of the Sun including the lower corona in EUV, the mid corona to 30 solar radii and the heliosphere beyond with the heliospheric imagers.

SOHO by itself demonstrates well the knowledge that can be garnered during an extended mission. The varying internal structure of the Sun, a major need for progress in understanding the solar dynamo, was unknown when SOHO was conceived, constructed, and launched. Observations by the GOLF and MDI instruments during the extended mission gave us measurements of the time-varying meridional flows that are believed to play a role in generating the solar magnetic field. Similarly, “local helioseismology” observations of the sub-surface structures of the Sun were unknown when SOHO was conceived, and have now become essential tools for the diagnostics of magnetic active region, while imaging of the farside of the Sun was unknown at the launch of SOHO, and has now become an essential space-weather forecasting tool. Some other important SOHO extended mission results include the discovery of coronal loop oscillations associated with CME passage; comprehensive solar observations of the major 2003 "Halloween" events, including the most intense solar flare of the last 30 years; demonstration of solar energetic particle event forecasting based on relativistic electron precursors; discovery of an acceleration of the solar convection zone meridional flow after the last solar maximum which may explain the marked decrease in solar polar magnetic flux compared with previous cycles.

But the Heliophysics System Observatory is not only solar-focused; it encompasses Sun-Earth connections and their consequences in key ways. The TWINS Mission-of-Opportunity continues to make stereo ENA images of the magnetospheric response to this increasing solar (and hence geomagnetic) activity. In the last year of its life the Ulysses extended mission established the whole-heliosphere existence of the unusual interplanetary conditions of the solar cycle 23 minimum, providing further impetus to the observations of the geospace responses to the 30% lower solar wind mass flux and magnetic field strength. The FAST mission was able to study the evolving magnetosphere-ionosphere coupling as the Sun’s activity wound down. While Polar was decommissioned prior to solar minimum, its extended mission allowed the exploration of the southern polar magnetosphere and provided complementary data for THEMIS studies of substorms. Extended mission components of the HSO also probe Earth’s ionosphere and thermosphere (CINDI, TIMED), as well as the mesosphere (AIM, TIMED), providing information both useful for science and relevant to national priorities such as climate change research, security, navigation systems, and communications. For example, SOHO and TIMED together provided solar EUV flux trends used to investigate the origin of the unusually low upper atmosphere densities that have influenced satellite operations in Earth orbit.

Beyond the Sun and the Sun-Earth connection, Voyager finally breached the boundaries of the heliosphere with in-situ observations to complement and provide ground truth for the global picture now remotely observed in ENAs by the Interstellar Boundary Explorer (IBEX) -which itself passes into extended mission later in FY11. Meanwhile, SOHO provided new measurements of the interstellar magnetic field, and SOHO and STEREO continue to be primary resources for comet discoveries and interplanetary dust studies.

To exploit the outstanding scientific opportunity presented by the long survival of well-built operating spacecraft that continue to produce valuable information for heliophysics researchers, NASA developed the Senior Review process, which provides orderly, peer-review assessments to aid decisions as to whether to continue funding each mission. This biennial event serves both to encourage long term science planning and operations strategizing by the NASA Heliophysics managers, and to provide the opportunity to determine what missions will continue to produce and which will be allowed to disappear from the Heliophysics System Observatory. As a result, both the community and NASA leaders gain further insight into the missions and their contributions, but this the Senior Review itself is faced with growing challenges related to increasingly unworkable budgetary constraints.

This challenge demands special consideration, especially in light of the growing value and use of multispacecraft investigations in heliophysics and the growing interest in whole-Sun, whole magnetosphere, whole heliosphere, and Sun-Earth connection observations and science. Only with the full HSO can we follow both quiescent and explosive activity from the Sun through the heliosphere and Earth's magnetosphere to the upper atmosphere, an unprecedented opportunity to attain the long-sought goal of understanding the heliosphere as a system. For example the extension of the STEREO mission now provides nearly whole-Sun images, allowing knowledge of the far side activity to be used for understanding Earth-perspective large scale solar phenomena as well as characterizing interplanetary conditions in other parts of the solar system. Simultaneously, extended mission observations from the two TWINS spacecraft provide nearly continuous imaging of the inner magnetosphere with frequent stereo viewing. The extended RHESSI mission is currently our only window on the highest energy X-rays and gamma rays generated by solar eruptions, providing unique information that complements Hinode, STEREO, and SDO observations of the same activity and constitutes a vital contextual link to HSO observations at Earth. For the first time solar energetic particle events can be routinely observed at 1 AU at several separated heliolongitudes while ACE and Wind continue to provide critical upstream measurements of the solar wind plasma, field, and particles that are about to impact the Earth. In addition, corotating high speed streams and stream interaction regions can be anticipated to provide opportunities for special campaigns of geospace observations or space weather forecasts. The need for these capabilities is particularly acute now that the Sun appears to be waking up from its unusually prolonged minimum. IBEX, viewing the edge of the heliosphere, benefits from the solar cycle-dependent 3D solar wind structure models validated with multipoint in-situ data provided by the Heliophysics System Observatory constellation, while the synergy between IBEX and the Voyagers at the edge of the heliosphere provides an irreplaceable observatory of these distant boundary regions, where the vast majority of galactic cosmic radiation is shielded from our solar system. Heliophysics researchers have become well-versed in accessing and using these multi-platform, multi-perspective, and multi-technique data sets and apply them routinely in constraining their theories and interpretations.

The great change that has occurred on the Sun in the past decade is another important reason to maintain our current constellation of Heliophysics missions. The photospheric magnetic field strength has dropped by a factor of two and has shown only weak signs of recovery. We have no precedent for this in the space age, although historical sunspot observations indicate a similar phenomenon in the early 1800s. If we are experiencing a repeat of this solar behavior, the Sun may take several cycles to recover its field strength and return to what we call normal activity as defined by cycles 21and 22. We need to keep measuring and analyzing this potentially paradigm-changing behavior and its planetary, terrestrial, and global heliospheric consequences with as much of the Heliophysics System Observatory as we can maintain.

Since at least the mid-1990s the NASA extended missions have been hampered by severely constrained resources for the PI teams that built and operate the instruments, and who know them and their data best. To perform any scientific analysis beyond the minimum necessary to validate the data flows, the PI team members and Co-Investigators now compete for analysis funding in the Guest Investigator, SR&T, TR&T, and Theory programs. Recent, devastating cuts in two of those programs have endangered our ability to continue to produce meaningful, new science that the novel and unique, spacecraft locations and the unusual solar activity make possible. Some of those cuts have been driven by "taxes" generated within NASA for initiatives outside Heliophysics, and others by the overall decrease in Heliophysics Mission Operations and Data Analysis (MO&DA) funding in the Administration budget. We need to restore the MO & DA level of effort and at a minimum, shield its most valuable assets, which include the extended missions within the HSO.

The 2010 Senior Review differed from the last two Senior Reviews in important ways. In the previous Senior Reviews the mission teams were asked to submit both ‘optimal’ and ‘in-guide’ budgets. The former allowed comparisons of the funding that would optimize the potential scientific impact of the missions against budgets adhering to the very tight fiscal constraints that NASA faces. Although the MO&DA budgets have never been sufficient to support all missions at the optimal level, it was the task of the Senior Review Panel to identify the missions that made the most compelling scientific cases for continuing operation and data analysis. However, in the 2010 Senior Review, mission teams were instructed to present only "minimal science" budgets. Moreover, the Senior Review Panel was informed of the need to cut the prospective MO&DA "minimal science" budget from \$59.5M to \$54.7M in FY11 and from \$57.9M to \$51.8M in FY12 to cover other areas of budgetary shortfall. The need for these reductions forced the Panel to undertake a line-by-line review of each mission's proposed budget, looking for places where funding could be cut even though the mission teams had already aggressively constrained their submitted cost projections. This process necessarily involved the Panel's judgments, generally on an instrument by instrument basis – a subjective exercise lacking in rigor for recommendations of such importance.

The Panel noted that while terminating satellites and/or instruments made obsolete by newer missions, such as SDO's replacement of TRACE and selected instruments on SOHO, made sense, the remaining missions in the Heliospheric System Observatory are complementary, not duplicative. Each mission occupies a unique vantage point, in terms of either its instruments and/or orbits. For example, the three spacecraft at L1 - SOHO, Wind, and ACE - carry distinct payloads. All of the HSO spacecraft and nearly all of the instruments are capable of returning high-quality data during the coming decade. Yet mature missions, especially those well into their extended phase, are targets for cuts since these missions already have a large database in hand. Such a viewpoint overlooks the new discoveries made possible by the synergies between old and new missions. As mentioned above, these give new combinations of diagnostics from multiperspective, multiwavelength images and coordinated imager and in-situ observations, together with the ability to investigate phenomena with both large and small spatial scales on a range of timescales. The decision making process also does not make allowances for 'discovery' class results and those that feed into major Heliophysics programs such as LWS and other areas of climate studies, astrophysics, planetary research, space weather forecasting enterprises in NOAA and DoD, and NASA's humans in space activities.

In summary, the Heliophysics System Observatory, including the extended missions, is the product of many years of effort and billions of dollars in investment poised to make new breakthroughs. But its existence and productivity depends on its support. The current Heliophysics Science Division budget allots only \$55M out of \$600M for operation of existing missions in 2011, with projections leaving them chronically undefunded by at least ~$5M/yr. While the need for and value of new missions such as Solar Orbiter and Solar Probe cannot be denied, $60M/yr for the entire suite of HSO missions (including those in extended phase) is a modest expenditure for what has become the primary engine of Heliophysics system science. The existing and extended missions together provide data critical for understanding the physics of the Sun and heliosphere, and the past, current and future conditions to which Earth and all the planets are exposed. The coincidence that the Sun has entered a period that is unprecedented, and that we are at the same time serendipitously endowed with a remarkable Heliophysics System Observatory begs to be exploited. The Heliophysics Discipline must strategize to find a way to maintain the operation, data collection and validation, and scientific data analysis of all spacecraft that are still sufficiently productive as determined by the Senior Review process. Adequate allowance must be planned into the discipline budget for the next decade for this purpose, and ways to minimize ongoing operations and data archiving costs investigated and enabled. Extended missions are demonstrably Heliophysics' best long term investment, with the greatest scientific return per dollar.

Low-impact space environment sensors required on every NASA space vehicle

Summary

There exists a class of space environment sensors that are designed to monitor the effects of space hazards for engineering concerns. They do not measure comprehensive aspects of the near-Earth space environment such as charged particle energy spectra, plasma composition, angular distributions, or high-energy ion composition. However, fielding these targeted sensors on every space vehicle would have two benefits: (1) the return of scientifically useful data from multiple points in the under-sampled Earth's magnetosphere and (2) directly applicable engineering data for the monitoring of space weather effects on the host vehicle in particular and across the entire active constellation of NASA vehicles in general. The scope of the proposal includes the requirement to field such low-impact sensors on every vehicle and the requirement to collect and synthesize the data in a centralized NASA repository. The availability of the information would benefit commercial, international, and US government stakeholders who own and operate active space systems.

Specific space environment hazards

We consider the impacts of vehicle charging, total ionizing dose, non-ionizing dose, and single-event effects. The relative importance of these hazards for a specific orbit is outside the scope of this paper and can be found in references such as Mazur [2003]. For example, interplanetary missions do not need to consider vehicle charging apart from the impact of charging in the solar wind on low-energy ion and electron science measurements; however interplanetary missions do consider the impacts of single-event effects from galactic cosmic rays and solar energetic particles. Missions in Earth orbit have more stressing environments, and it is the awareness of near-Earth space weather that would be of highest priority because of the number of space assets in the magnetosphere. See Mazur [2003] for an example of the mapping of these hazards to various orbits.

Scope of targeted sensors and examples

Targeted sensors have low size, weight, & power, provide space situational awareness for host vehicle, and are focused on effects [O'Brien et al. 2008]. The table below compares the resource requirements for several targeted examples and other more comprehensive science payloads.

Sensor Name	Type[1]	Mass (kg)	Telemetry Rate (b/s)	Platform(s)	Orbit	Hazards	Provider	Ref.
CEASE CEASE-II	T	1.0	1.3	TSX-5 DSP-21	LEO GEO	Dose, Charging, SEE	AFRL	Di98
BDD CXD	T	6.8 3.5	0.5	GPS	MEO	Dose, Dose Rate, SEE	LANL	Ca98 Tu04
CPA	T	0.15	10	Intelsat	GEO	Charging	Lockheed Martin	Bo95
Merlin	T	1.0		Giove-A	MEO	Dose, Charging, SEE	Qinetiq	
ADS02 chip dosimeter	T	0.02	0.13	LRO (launch Nov 2008)	Lunar	Total Dose	Aerospace	Ma07
DOS+SCM+HILET	C	8.9 total mass	45000	Classified platform	HEO	Dose, Charging, SEE	Aerospace	Ma04
SEM	C	15.0	96	NOAA/POES	LEO	Dose, Charging, SEE	NOAA	
SEM	C		~0.5	NOAA/GOES	GEO	Dose, Charging, SEE	NOAA	An96
CPA+SEE MPA+SOPA+ESP	C	3.5 per box	1500 per box	LANL	GEO	Dose, Charging, SEE	LANL	Mc98;Me96Be96
SSJ4/5	C	3.2	360	DMSP	LEO	Charging	AFRL	SC88
SABRS ZEP+ZPS	C	~9 total mass	Up to 20,000	Various	Various	Dose, Charging, SEE	LANL	

Notes:

1. T=Targeted; C=Comprehensive.

Table 1. Examples of targeted and comprehensive space environment sensors.

Within this range of existing sensor class there is a wide-range in sensor mass, but as the table indicates, these packages are on the tail of the distribution for typical space science experiment resources.

As an example of the usefulness of a targeted sensor, we show in the figure below a comparison of a compact monitor of differential surface charge with concurrent measurements from a nearby science payload on one of the LANL space vehicles in geostationary orbit. In this case the scientific phenomenon of interest is a substorm injection of hot electrons [Ozkul et al. 2001]; the engineering phenomenon of interest is the resulting spacecraft frame and differential surface charging effects.

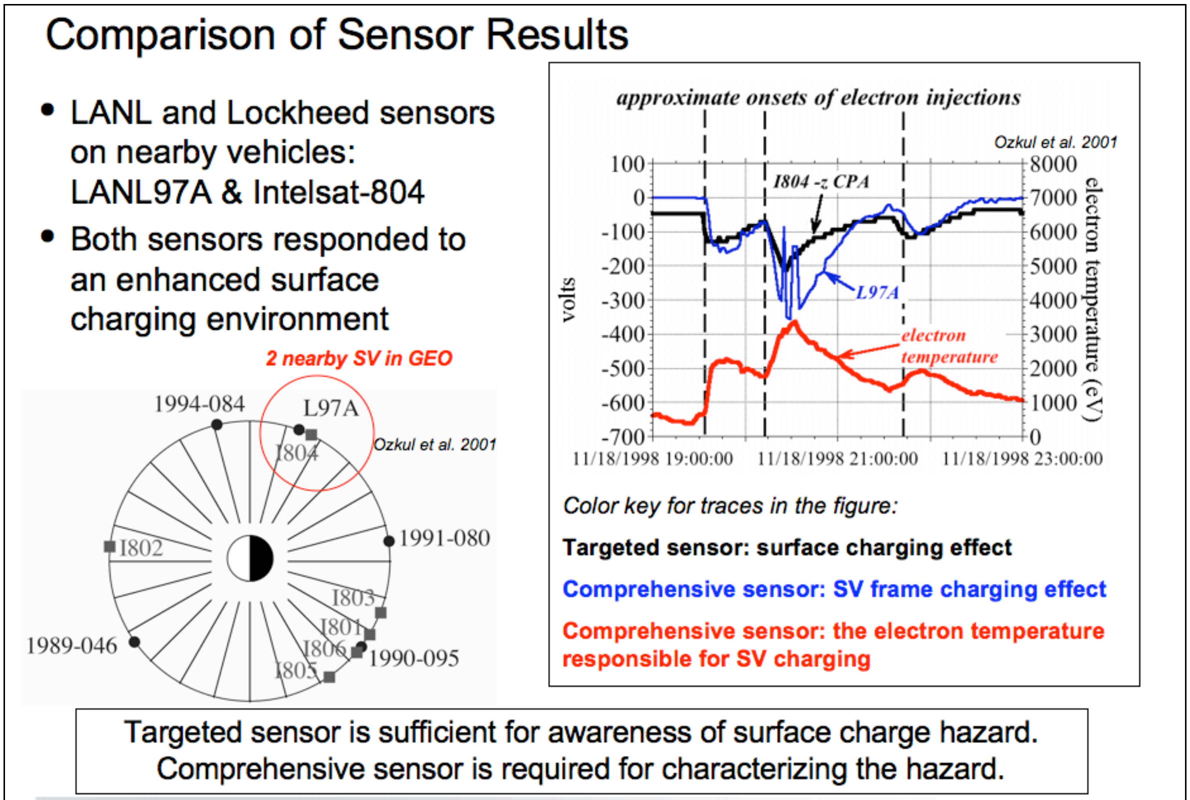

Figure 1. Comparison of data for vehicle charging and directly-measured electron temperature in a substorm injection observed at geostationary orbit.

The host spacecraft thus benefits from the situational awareness of an important space weather hazard while the research and operations communities both benefit from the monitoring of the substorm electron temperature at many points within the plasmasheet. We note that one outcome of the analysis of several existing charge monitors in geostationary orbit was that the electron temperature varies on the spatial scale of 1e03 km, thus measurements of the charging environment at one vehicle could not be used to predict the environment anywhere else.

We suggested the requirement that every space vehicle carry targeted environment sensors; this should be the case regardless of the number of existing sensors in that orbital regime (e.g. low-Earth orbit) and should be implemented as a standard mission requirement in the same way that missions require a thermal design, thermal balance test, and on-orbit monitoring of subsystem temperatures. Extremely resource-constrained missions such as Solar Probe Plus would not be exempt but not all hazards relevant for that mission; total ionizing dose,non-ionizing dose, and single-event effects would apply.

Need to insure a unified space and ground system

The other requirement we mentioned is that of a ground system to collect, process, and disseminate the data from multiple targeted space weather sensors. Without a clearly defined system, the data would likely not see use beyond the particular NASA program that fielded the sensors. For example, if the Earth-observing system had such sensors, their data and resulting situational awareness should be accessible to the Heliophysics community for scientific research into fundamentals of the Sun-Earth connections as viewed from low-Earth orbit.

Potential resistance modes

Any requirement for a space mission that doesn't originate within the home division will likely meet resistance. Here are a few examples of responses we have come across in our experiences in National Security Space and in commercial applications:

- Prime contractor should be most interested in the data, so they should pay
- Mission doesn't have a requirement to monitor space weather so it will not happen on my watch
- Prime sensors already measure the space environment so additional engineering sensors aren't required

One option for an overall strategy puts the responsibility of acquiring and disseminating the targeted data in a distinct NASA entity, however the details of implementation are outside our scope. The CCMC is a model for multi-agency interest in space weather models, and indeed the data from many targeted sensors would be useful for some existing CCMC and future models. Perhaps an augmentation to the CCMC program to require and acquire targeted sensors (thus needing participation from the NASA spacecraft engineering community), and to collect the data, would be a logical approach.

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Unintended effects of increasing reliance on science requirements

Summary

NASA science missions are increasingly tracked with project management systems that establish and monitor requirements for science in the same way that engineering requirements and DOD mission requirements are tracked and managed. The motivation for the approach is that project costs increase with requirements creep, therefore early establishment of the requirements and the measure of any engineering or science change relative to the requirements will insure against increases in project scope and therefore cost.

There are several unintended consequences of this management approach to science that in recent experience have had negative effects on mission success.

Assessment of effects on recent projects

- Projects spend more time and money tracking requirements instead of Phase-A and B activities that would actually decrease mission cost and risks.

For example, apart from the increased management burden on the project office and the instrument teams, the establishment of excessively detailed requirements and their flowdown takes time and effort away from other early actions that can reduce mission risks. The procurement and testing of critical EEE parts, for example, early in the instrument design would have significantly greater impact on schedule and budget than requirements management. Teams that design and build particle sensors often procure silicon detectors well before instrument CDR because the devices are often custom designs and have 6 month or longer lead times. Thus there is precedent for procuring flight hardware long before the flight design is technically passed in review. There would be greater benefit of constructing prototype hardware even as early as Phase-A in order to tease out the potential difficulties with parts vendors.

- Science investigations are often proposed based on an existing capability, so there is extra and needless work to force the capability to appear as flowing from requirements

Requirements for capability-driven science should be a floor below which the instrument performance should not fall, but should not be created just to satisfy the requirements-driven structure of the project. Instrument proposals are often the result of the community's capability to make a particular measurement; in this case some instrument is the best the science community has to offer, and that is what NASA has chosen implement on a science mission. To then recast the measurement as flowing from a specific level-1 requirement is a needless exercise because the instrument has already been selected for the mission. The unintended effect is the expense of time and effort to develop a requirements structure that has little relevance to design trades for the instruments.

- Project management satisfies its own goals of establishing and tracking requirements with the unintended consequence of failing to uncover the actual risks to the mission

NASA project management has blossomed into a self-fulfilling system wherein reviewers rely on document generation and value tracking instead of engaged, goal-oriented systems engineering and mission assurance. This tick-the-box mentality leads to required project documents being promptly entered into a management system but not actually being read by the recipients in a timely manner. This leads to multiple requests for the same information, redundancy where it matters the least, and a reliance on the computer system instead of on trained and experienced workforce of scientists and engineers.

When attempting to address these unintended consequences it is paramount to recognize that in the context of a science mission, in which each instrument PI will be among the primary users of the instrument data, there is no one more motivated to see the instruments and mission succeed than the PI. That enthusiasm and passion must be engaged and exploited rather than thwarted by a hollow and bureaucratic project management system.

Nowcast of Atmospheric Ionizing Radiation for Aviation Safety

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Abstract

The Nowcast of Atmospheric Ionizing Radiation for Aviation Safety (NAIRAS) is a prototype operational model for predicting commercial aircraft radiation exposure from galactic and solar cosmic rays [*Mertens et al., 2008, 2010*]. The NAIRAS model addresses an important national need with broad societal, public health and economic benefits. The prototype development is currently funded by the NASA Applied Sciences / Aviation Weather Program. The anticipated completion date of the operational prototype is June 2011. In this white paper we propose a research-to-operations activity to transition NAIRAS to operations. In addition, during the prototype development phase, the NAIRAS team has identified new science questions that must be addressed in order to obtain a reliable and robust operational model of atmospheric radiation exposure. Thus, we also propose an operations-to-research activity that addresses emerging science questions concomitant with the research-to-operations activity.

1. Introduction

An important atmospheric state variable, driven by space weather phenomena, is the ionizing radiation field. The two sources of atmospheric ionizing radiation are: (1) the ever-present, background galactic cosmic rays (GCR), with origins outside the solar system, and (2) the transient solar energetic particle (SEP) events (or solar cosmic rays), which are associated with eruptions on the Sun's surface lasting for several hours to days with widely varying intensity. Quantifying the levels of atmospheric ionizing radiation is of particular interest to the aviation industry since it is the primary source of human exposure to high linear energy transfer (LET) radiation. High-LET radiation is effective at directly breaking DNA strands in biological tissue, or producing chemically active radicals in tissue that alter the cell function, both of which can lead to cancer or other adverse health effects [*Wilson et al., 2005a, 2003*]. Adverse health effects include, but are not limited to, reproductive disorder and prenatal injury [*Lauria et al., 2006; Waters et al, 2000; and Aspholm et al., 1999*]. The International Commission on Radiological Protection (ICRP), the Environmental Protection Agency (EPA), and the Federal Aviation Administration (FAA) classify crews of commercial aircraft as radiation workers [*McMeekin, 1990; ICRP, 1991*]. It's estimated that, on an annually basis, aircrew are exposed to considerably more radiation than the average nuclear power plant worker [*Wilson et al., 2003*]. However, aircrew are the only occupational group exposed to unquantified and undocumented levels of radiation. Furthermore, the current guidelines for maximum public and prenatal exposure can be exceeded during a single solar storm event for commercial passengers on intercontinental or cross-polar routes, or by frequent use (~ 10 flights per year) of these high-latitude routes even during background conditions [see also, *Dyer et al., 2009; Copeland et al., 2008; AMS, 2007*]. As a result, there is a need for a capability to predict real-time radiation levels for the commercial aviation industry.

Over the last decade, airspace over Russian and China has opened up to commercial traffic, allowing for polar routes between North America and Asia [*AMS, 2007*]. These cross-polar routes reduce flight time and operational cost; thus, the number of cross-polar commercial routes has increased exponentially. The typical cost savings from a cross-polar route from the US to China is between $35,000 and $45,000 per flight compared to the previous non-polar route [*DOC, 2004*]. However, the polar region receives the largest quantity of radiation because the shielding provided by Earth's magnetic field rapidly approaches zero near the magnetic pole. On the other hand, the economic loss to an airline to reroute a polar flight can be a factor of three greater than the original cost-savings of flying the polar route if fuel stops and layovers are necessary. Thus, the cost to reroute a cross-polar route can be as much as $100,000 per flight [*DOC, 2004*]. Consequently, an aircraft radiation prediction model must also be accurate to minimize radiation risks while simultaneously minimizing significant monetary loss to the commercial aviation industry.

The goal of the NAIRAS model is to provide a new decision support system for the NOAA Space Weather Prediction Center (SWPC) that currently does not exist, but is essential for providing the commercial aviation industry with data products that will enable airlines to achieve the right balance between minimizing flight cost while at the same time minimizing radiation risk. Thus, NAIRAS model addresses an important national need with broad societal, public health and economic benefits. For example, during the Halloween 2003 storm period the FAA issued an advisory that high-latitude flights were subject to excessive levels of radiation exposure. One major airline was cautious and rerouted six polar flights to non-polar flights requiring fuel stops in Japan and/or Anchorage [*DOC, 2004*]. Rerouting polar flights can add an additional cost to airlines up to $100,000 per flight if fuel stops are necessary. However, the actual radiation levels did not pose a significant risk during this storm period [*Mertens et al., 2010; Copeland et al. 2008*]. If the NAIRAS model had been available at this time, it could have potentially saved this airline up to $600,000. On the other hand, the radiation levels during the January 2005 storm period were sufficient to exceed the guidelines for maximum annual public and prenatal exposure [*Copeland et al., 2008*], and the availability of the NAIRAS model could have provided the guidance to minimize the radiation risk from this SEP event.

NOAA/SWPC enthusiastically embraces NAIRAS as a viable candidate for operations at the National Weather Service [*Bogdan et al., 2010*]. However, a robust verification and validation (V&V) program is needed as part of the transition to operations activity in order to demonstrate the robustness and efficacy of the NAIRAS model over the full dynamic range of space weather conditions. In addition, in developing the NAIRAS operational prototype, the NAIRAS team has identified new science questions that must also be addressed before full operational implementation. These topics are discussed in more detail in sections 3 and 4. In the next section we describe the major components of NAIRAS model and the model/data system architecture.

2. NAIRAS Distributed System Architecture

The NAIRAS model is based on analytical-numerical solutions of couple Boltzmann transport equations, which are solved on a global grid and in real-time at a 1-hour time cadence [*Mertens et al., 2010*]. The solutions of the transport equations are obtained using NASA Langley Research Center's HZETRN code [*Wilson et al, 1991, 2005b*]. Effective dose and ambient dose equivalent are computed using neutron and proton fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients, respectively, tabulated by *Ferrari et al.* [*1997a, 1997b*]. The dosimetric contributions from the other ions are obtained by scaling the proton conversion coefficients by Z^2_j according to the stopping power dependence on charge. Geomagnetic shielding specified by vertical cutoff rigidity is calculated from the model of *Kress et al. [2010]*, which is based on the Tsyganenko and Sitnov TS05 magnetospheric magnetic field model [*Tsyganenko and Sitnov, 2005*]. The real-time input data used by the cutoff rigidity model are Dst, and solar wind dynamic pressure and interplanetary magnetic field data measured by the NASA/ACE satellite. The cutoff rigidities are also calculated on a global grid and in real-time at a 1-hour time cadence. Solar cycle modulation is taken into account using an extension to the Badhwar and O'Neill GCR model [*O'Neill, 2006*]. The GCR model propagates the local interstellar spectrum of each element of the GCR composition from outside the heliosphere to 1 A.U. and, thus, provides the fluence rate boundary conditions for transport through the magnetosphere and atmosphere using the cutoff rigidity and HZETRN codes, respectively. The Badhwar and O'Neill model was extended by fitting the solar modulation potential to high-latitude, real-time neutron monitor count rate measurements. The real-time neutron monitor measurements currently used by NAIRAS in the GCR model are Oulu, Thule, Lomnicky, and IZMIRAN. During SEP events, NOAA/GOES ion flux measurements and NASA/ACE low-energy proton flux measurements are used in a spectral fitting algorithm to derive the SEP ion fluence rate boundary conditions for transport through the magnetosphere-atmosphere system. Real-time NCEP Global Forecasting System (GFS) meteorological data are used to specify the overhead shielding by the atmospheric mass.

Due to insufficient community funding for research-to-operations activities, the NAIRAS operational prototype model has adopted the distributed network paradigm – automated systems of models, data streams and algorithms at multiple, geographically dispersed facilities linked by operational servers [*Tobiska, 2009*]. Space Environment Technologies (SET) developed the critical input data stream formats and I/O interface modules between the input datasets and the SET server database. There are two redundant sources for each input dataset to ensure operational continuity. SET processing of the input data is continuous and a 4-day buffer for the 1-5 minute cadence input data are maintained on the SET server. The NAIRAS code runs continuously at NASA Langley Research Center (LaRC). When the NAIRAS code is ready for a new 1-hour update, the code automatically retrieves the required input datasets from the SET server. After NAIRAS has finished computing the global radiation exposure quantities for the current 1-hour period, the radiation exposure data are further processed and graphical and tabular data products are derived. These derived products are pushed back to the SET serve for dissemination and are available at the NAIRAS public web site (http://sol.spacenvironment.net/~nairas/index.html). Currently, NAIRAS is operating in a 4-hour demo mode until the code is completely ported and tested at LaRC Atmospheric Sciences Data Center.

3. Emerging Science Questions

In the process of developing the NAIRAS prototype, a number of new science questions have emerged that need to be adequately addressed in order to obtain a reliable and robust operational aircraft radiation exposure prediction model. One new science question concerns how to account for the high-energy tail of the incident SEP ion spectral fluence rates. The highest energy GOES ion flux measurements (~ 500 MeV/n) can vary by more than an order of magnitude over the duration of a SEP event [*Mertens et al., 2010*]. Because there are no GOES measurements greater than ~ 500 MeV/n, the high-energy tail of the SEP ion spectral fluence rates, determined by our spectral fitting algorithm, are unconstrained. Therefore, the high-energy tail is subject to orders of magnitude uncertainty. During the January 20, 2005 SEP event, the equatorial neutron monitor station at Tibet (cutoff rigidity ~ 14.1 GV) registered a Ground-Level Enhancement (GLE), indicating a sufficient number of ~ 14 GeV SEP protons to increase the baseline neutron monitor count rate by 2.4% [*Plainaki et al., 2007*], indicating the possibility of very high-energy SEP protons that cannot be measured by satellite. As a result of the large uncertainties in the high-energy SEP ion spectra from satellite measurements, the atmospheric radiation exposure rates will be subject to orders of magnitude of uncertainty. *Dyer et al. [2009]* has noted that retrospective model calculations of atmospheric radiation exposure during SEP events have differed by up to an order of magnitude.

Another new science question concerns how to account for spatial anisotropy in the incident SEP ion flux. The January 20, 2005 was a recent SEP event that exhibited large anisotropies. This is evident by the fact that only the Tibet neutron monitor station registered a GLE at equatorial latitudes (i.e., at very high energy) [*Plainaki et al., 2007*]. *Matthia et al. [2009]* showed that the anisotropy persisted for more than 12-hours during this event. The peak incident SEP proton flux and atmospheric radiation exposure rates occurred at the beginning of this event in the southern hemisphere only. SEP spatial anisotropy can also introduce large uncertainties in atmospheric radiation exposure predictions if an isotropic distribution is assumed, as is typically done [*Dyer* *et al., 2009*]. Currently, NAIRAS assumes that the SEP ion flux is isotropic, with a factor of one-half applied to account for Earth shadowing.

We propose to account for SEP spatial anisotropy and the SEP high-energy tail by utilizing data from a world-wide distribution of neutron monitor stations. We will develop robust, automated algorithms suitable for real-time application. This is now possible by the recent availability of a world-wide network of real-time neutron monitor data [*Mavromichalaki et al., 2005*], and generalized neutron monitor yield functions [*Fluckiger et al., 2008*]. Neutron count rates measured by a neutron monitor station can be simulated by convolving the incident cosmic ray spectrum with a yield function specific to the neutron monitor site, which depends primarily on atmospheric depth at the altitude of the site and on the cutoff rigidity at the geographic location of the site [*Matthia et al., 2009; Fluckiger et al., 2008; Vashenyuk et al., 2007; Cramp et al., 1997*]. Our nominal SEP spectral fitting algorithm that uses the GOES and ACE ion flux measurements will be augmented with neutron monitor data. This will enable the incident SEP proton fluence rate to be fit from ~ 100 keV to ~10 GeV and alphas from ~ 1 MeV to ~ 5 GeV. We can quantify the improvement made by utilizing the neutron data by comparing measured and calculated neutron counts rates at neutron stations not used in developing the incident SEP spectra fit. In accounting for SEP spatial anisotropy, we will explore the efficacy of assuming a Gaussian or a linear dependence on the pitch-angle distribution [*Vashenyuk et al., 2007; Matthia et al., 2009*]. We will decide on the best approach by comparing measured and calculated neutron counts rates at neutron stations not used in developing the fit in pitch-angle distribution.

There are several new science questions regarding the modeling of cutoff rigidities [*Kress et al., 2010*]. Our recent analysis of the Halloween 2003 storm period showed that the radiation exposure rates at commercial and executive jet cruising altitudes are highly sensitive to the cutoff rigidity, especially along the open-closed magnetosphere boundary [*Mertens et al., 2010*]. *Kress et al. [2010]* demonstrated that the uncertainty of the state-of-the-art in calculating the cutoff latitude for ~ 20 MeV protons is around two degrees in latitude. If this uncertainty is indicative of the uncertainty in modeling the location of the open-closed magnetosphere boundary, then the prediction of aircraft radiation exposure for international flights along the North Atlantic corridor connecting the US and Europe can have uncertainties greater than a factor of two [*Mertens et al., 2010*]. The NOAA/POES mid-energy proton flux data are available in real-time and we will explore the possibility of using these measurements in a data assimilation capacity to better constrain the cutoff model. We'll also explore if a non-uniform grid, such as the distorted spherical grid, can better resolve the cutoff variation with latitude.

Another important science topic is the role of anisotropy in representing the local cutoff rigidity. The previous discussion on anisotropy dealt with large-scale variations in the global distribution of incident SEP ion flux. Here we refer to small-scale, local variations: i.e., the variation of the cutoff rigidity with solid angle in computing the number of ions arriving in the atmospheric at a particular geographic location and altitude. We compute a vertical cutoff rigidity at a single altitude and assume it does not vary locally with altitude or solid angle, which are the usual assumptions [*Kress et al., 2010*]. These assumptions work well at the Earth's surface, but become less accurate with increasing altitude. The issue in real-time applications is that it is impractical to compute by rigorous numerical particle trajectory simulations a global grid of cutoff rigidities as a function of altitude and solid angle at each geographic grid point. We will quantify the uncertainty in these assumptions on GCR and SEP atmospheric radiation exposure rates and assess if simple angle-altitude scaling using Stormer theory can adequately reduce the uncertainty, or develop other alternatives [*Kress et al., 2010*].

We will assess the reliability and feasibility of predicting the real-time geomagnetic cutoff rigidities using the physics-based LFM MHD magnetic fields. The LFM MHD code may be run as a stand alone model or coupled with other geospace models currently under development within CISM. For example, the LFM magnetospheric magnetic fields may be coupled with the Thermosphere-Ionosphere Nested Grid (TING) model [*Wang et al., 2004*] and/or with the Rice Convection Model (RCM) [*Toffoletto, 2004*], which models the ring current. The semi-empirical TS05 model provides more accurate cutoff rigidities than the stand alone LFM MHD model, as determined by comparisons with satellite observations during a Halloween 2003 geomagnetic storm [*Kress et al., 2010*]. This is mainly due to the lack of a full kinetic description of the ring current in the MHD model, which typically causes the LFM fields to be too high. We anticipate that the fully coupled LFM-RCM-TING model currently under development will significantly improve the simulations of cutoff rigidities compared to the stand along LFM MHD model. Furthermore, the physics-based LFM-RCM-TING model will be able to incorporate short time-scale dynamics not included in empirical magnetospheric magnetic field models. When the code development within CISM reaches sufficient maturity, we will assess the influence of short time-scale magnetospheric dynamics on the atmospheric ionizing radiation field using the fully coupled LFM-RCM-TING model.

4. Transition to Operations

As stated previously, NOAA/SWPC enthusiastically embraces NAIRAS as a viable candidate for operations at the National Weather Service [*Bogdan et al., 2010*]. However, a robust V&V program is needed as part of the transition to operations activity in order to demonstrate the robustness and efficacy of the NAIRAS model over the full dynamic range of space weather conditions. We propose a three-pronged, comprehensive V&V program with a path towards real-time data assimilation of global onboard aircraft radiation measurement to improve NAIRAS predictions, in much the same way that meteorological weather forecasts models ingest real-time atmospheric state variable measurements to constrain and improve their forecasts.

The first prong of our three-pronged V&V plan is to compare NAIRAS with historical aircraft measurements made by Tissue Equivalent Proportional Counter (TEPC) instruments, or compare with other models when possible. TEPC instruments measure the ambient dose equivalent rate, which is a reasonable proxy for the dosimetric quantity directly related to biological risk – the effective dose rate [*Clucas at el., 2005*]. NIOSH has agreed to provide the NAIRAS team with TEPC measurements for 32 flight segments under background GCR conditions. The German Aerospace Corporation (DLR) has provided TEPC measurements for a few flight segments. In addition, it may be possible to obtain aircraft TEPC measurements from Dachev et al., Spurny et al., and Lewis et al.

The second prong of our three-pronged V&V plan is to establish collaboration with the NASA Stratospheric Observatory For Infrared Astronomy (SOFIA) Program. SOFIA is an airborne (Boeing 747) observatory of infrared telescopes and instruments for astrophysics and astronomy research. The SOFIA aircraft will fly approximately 1000 hours per year at various latitudes, longitudes, and altitudes, reaching altitudes over 40 kft, and will make observations for two decades. The SOFIA mission provides an extraordinary collaborative opportunity between the Astrophysics, Heliophysics, and Applied Science communities, through the addition of radiation instruments on the SOFIA aircraft, to conduct NAIRAS V&V analysis over two solar cycles. These long-term measurements, combined with the extensive altitude range, will enable solar cycle modulation and cutoff rigidity effects to be separated out. As a result, the fundamental mechanisms and cross sections that produce the showers of secondary particles can be quantitatively assessed. The SOFIA mission provides an opportunity to conduct physics-based V&V of the NAIRAS model.

The third prong of our three-pronged V&V plan is to make new automated onboard TEPC measurements with a path toward global, real-time data assimilation of these measurements into the NAIRAS model. This approach will be implemented in three phases. In Phase I (~ 1-2 years), we will deploy a TEPC instrument on three flights: domestic cross country flight, high-latitude flight connecting the US with Europe, and a polar flight. High-latitude TEPC measurements are not widely available and to our knowledge no radiation measurements have been made along a polar route. FedEx has agreed to cooperate with us and the three TEPC measurements will be conducted on FedEx flights. The TEPC instrument and data analysis will be provided by our team members at CREESE and Boeing [*Gersey et al., 2002, 2007a-b*]. This first phase provides initial NAIRAS V&V for the high-latitude and cross-polar routes, and also provides a technology demonstration of new ways advanced by our CREESE team member of quantifying the important neutron contribution to radiation exposure and biological risk. In Phase II (~ 2-5 years), continuous TEPC measurements will be made on perhaps a dozen aircraft, and the data will be transmitted to the ground through aviation systems such as AirDat's network of airborne sensors called Tropospheric Airborne Meteorological Data Reporting (TAMDAR), which provide a continuous stream of real-time observations. This phase enables extensive V&V for quantitative characterization of the NAIRAS model uncertainties as is necessary for data assimilation. Moreover, this phase enables the design and the implementation of the software for which the SET distributed network system serves as the communication nerve center and I/O data hub between the real-time onboard radiation measurements and the NAIRAS model predictions. CREESE and Boeing will participate in developing the interface software between the TEPC instruments and the real-time aircraft data downlink, and develop analysis tools to monitor and assess the health of the instruments. Phase III (~ 3-5 years) will be a large-scale implementation of Phase II into operations, with data assimilation capacity, that will dramatically improve aviation radiation health and safety while simultaneously providing economic benefit to the aviation industry.

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Ionospheric E-Region Chemistry and Energetics

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Abstract

We propose an Earth-observing, multi-satellite science mission to explore the last remaining frontier in upper atmospheric research – the ionospheric E-region. A quantitative understanding of the E-region is essential to understanding the state of the entire global ionosphere-thermosphere system, yet it is the only atmospheric region that has not been observed and quantitatively analyzed globally. The E-region science mission leverages off the heritage of the TIMED mission and the concept team contains the expertise necessary to develop the proposed instruments and to derive the science data products.

1. Scientific Background

The last remaining frontier in global space-born atmospheric observations is the ionospheric E-region from about 100 to 160 km. In this altitude region, solar EUV photons deposit most their energy, and at high-latitudes magnetospheric energy supplied by the solar wind is dissipated in large quantities via particle precipitation and Joule heating [*Wilson et al., 2006*]. Moreover, the largest sources of radiative cooling in the quiet-time ionosphere-thermosphere (IT) system are infrared emission by NO at 5.3um and CO2 at 15 um and 63 um [*Roble, 1995*]. During solar-geomagnetic storm disturbances, NO 5.3 um and NO+ 4.3 um emission are the largest sources of infrared radiative energy dissipation [*Mlynczak et al., 2005; Mertens et al., 2008*]. Thus, the E-region contains the largest sources and sinks of radiative energy in the IT system and a quantitative understanding of the radiative heating and cooling rates is essential to understanding the energy flow, composition, and dynamics of the global IT system.

In addition to the radiative and electrodynamic energy deposition described above, chemical processes are another source of heating in the E-region [*Rees et al., 1983*]. Exothermic ion-neutral reactions, odd-nitrogen chemistry, and the quenching of metastable states are all sources of chemical heating that obtain their maximum deposition rates below 200 km. The neutral gas heating efficiencies depend on the total density, temperature, and ion and neutral composition of the IT system. An understanding of the thermal and chemical state of the E-region is essential for a quantitative understanding of the IT system in general, and ion-neutral coupling mechanisms in particular.

The E-region is also an important atmospheric layer for understanding the dynamical coupling between lower atmospheric wave disturbances and upper atmospheric electrodynamics, particularly in the equatorial region. The upward propagating atmospheric tides reach their maximum amplitude in the E-region between 100 and 120 km before being dissipated by molecular processes [*Forbes et al., 2008*]. These tidal perturbations modulate the E-region dynamo electric fields and the subsequent plasma properties via vertical drift perturbations. Furthermore, there is some evidence that planetary wave oscillations in the E-region zonal winds are the source of oscillation of the evening zonal E-region electric field and F-region vertical drift [*Abdu et al., 2006*]. This suggests that the E-region plays an important role in understanding the day-to-day quiet-time variability of the equatorial spread-F phenomena and plasma bubble occurrence and intensity.

The global IT system is disturbed during solar-geomagnetic storms [*Deng and Ridley, 2007*]. High-latitude energy deposition by particle precipitation and Joule heating increases the neutral temperature, which causes an upwelling of the neutral atmosphere and a subsequent large-scale disturbance of the global IT atmospheric circulation [*Fuller-Rowell et al., 1994*]. Thus, the enhanced energy dissipation in the high-latitude E-region during solar-geomagnetic activity is coupled to changes in the E-region thermal structure, chemistry, dynamics, neutral and plasma composition, and electrodynamics at low- and mid-latitudes [*Fuller-Rowell et al., 1994; Richards, 2004; and Fernandez et al., 2010*]. An understanding of the E-region is central to a quantitative understanding of global ionospheric storm effects.

2. **Current State of Knowledge and Motivation for New Mission**

An incontrovertible boon to the mesosphere, lower thermosphere, and ionosphere (MLTI) community followed from the successful launch and operation of the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. The TIMED satellite payload is comprised of four instruments. The two TIMED instruments important for this proposal are the Global Ultraviolet Imager (GUVI) and the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instruments.

The GUVI instrument has provided profound new insight into the dynamical response of the neutral and plasma composition of the global IT system to solar and magnetospheric forcing. Data from the GUVI instrument have been used to analyze the total energy flux and characteristic energy of auroral electrons during geomagnetic storms [*Christensen et al., 2003*], seasonal variations in quiet-time global O/N2 [*Strickland et al., 2004a*], specification of solar EUV energy flux shortward of 45 nm under flare and non-flare conditions [*Strickland et al., 2004b, 2007*], the causal mechanisms responsible for dayside and nightside detached auroras [*Zhang et al., 2004a, 2005a*], the influence of solar wind conditions on cusp auroras [*Zhang et al., 2005b*], the dynamics of electron and proton auroras [*Zhang et al., 2006b, 2005c*], anomalous nighttime thermospheric FUV emissions from energetic neutral atom precipitation [*Zhang et al., 2006a*], and the effects of magnetic storms on the thermospheric neutral composition [*Meier et al., 2005; Crowley et al., 2006; and Zhang et al., 2004b*].

SABER data have mostly been used to study the mesosphere. The exceptions are thermospheric tidal studies up to 120 km [*Forbes et al., 2008; Zhang et al., 2007*] and thermospheric infrared emission studies during quiet-time [*Mlynczak et al., 2008, 2009; Mertens et al., 2009a*] and during solar-geomagnetic storm periods [*Mlynczak et al., 2005; Mertens et al., 2007, 2008, 2009b*]. SABER has provided the longest continuous observations of thermospheric infrared emission, and the extraordinary storms of solar cycle 23 have yielded unprecedented discoveries in IT infrared energetics and E-region ion-neutral coupling. For example, the SABER NO 5.3 um measurements were enhanced by a factor of 6 to 10 during the April 2002 storm event [*Mlynczak et al.,* 2005]. Storm-time enhancements of NO(v) 5.3 um emission is the primary mechanism of dissipating solar storm energy in the thermosphere. Thus, NO(v) 5.3 um emission is considered to be a "*natural thermostat*" by which heat and energy are lost from the thermosphere to space and to the lower atmosphere.

Shortly following the analysis of SABER 5.3 um emission, unexpected insight into the IT storm-time response came about through observation and analysis of the several orders of magnitude enhancement in the nighttime SABER 4.3 um measurements. SABER observations and data analysis revealed that nighttime 4.3 um radiance is dominated by $NO^+(v)$ emission during geomagnetically disturbed conditions [*Mertens et al.*, 2009a-b, 2007a]. Three important discoveries followed. One, since NO^+ is the terminal E-region ion, by charge neutrality, the $NO^+(v)$ 4.3 um emission is also an excellent proxy suitable for deriving an empirical model of storm-time enhancements of the E-region electron densities [*Fernandez et al.*, 2009; *Mertens et al.*, 2007a-b]. Two, analysis of SABER $NO^+(v)$ 4.3 um emission led to major advances in the understanding of E-region ion-neutral chemistry and kinetics. *Mertens et al.* [2008] demonstrated for the first time that O_2^+ + NO charge transfer produces $NO^+(v)$. This mechanism identifies a new source of auroral infrared emission at 4.3 um, which also happens to be the dominant source of $NO^+(v)$ excitation and auroral 4.3 um emission below 160 km. The role of this mechanism in auroral 4.3 um emission provides a new context for understanding auroral $O_2(^1\Delta)$ 1.27 um emission, since $O_2(^1\Delta)$ can be directly excited by the O_2^+ + NO charge transfer reaction or formed by collisional quenching of $O_2(^1\Sigma)$ excited by the former charge transfer reaction. Third, $NO^+(v)$ 4.3um emission is the second largest contribution to solar-geomagnetic infrared radiative energy loss and provides a non-negligible contribution to the "natural thermostat" thought, for the most part, to be solely due to NO(v) 5.3 um emission.

Despite these recent discoveries, the broadband infrared measurements of SABER limit the ability to probe the details of the physical and chemical excitation and loss processes, which are necessary for a complete physical description of infrared radiative emission by NO(v) and $NO^+(v)$ – the largest sources of energy dissipation in the IT-system. Detailed information on the fundamental excitation and loss processes is embedded in the infrared spectrum, of which SABER only provides an integral constraint via its broadband measurements. In order to advance our understanding of IT chemistry and energetics beyond the current state of knowledge, spectral infrared measurements over a wide spectral range are required. Furthermore, these measurements offer the potential to develop new retrieval methodologies for extending temperature and density profiling above 120 km while simultaneously reducing the reliance on accurate knowledge of non-local thermodynamic (non-LTE) mechanisms and input parameters as compared to SABER non-LTE temperature retrievals.

There are additional limitations of the TIMED mission that preclude a quantitative understanding of the physical and chemical mechanisms responsible for E-region energy deposition and infrared response, which govern the energy transport, composition, and dynamics of the IT system. GUVI and SABER do not simultaneously observe the same atmospheric volume. Nevertheless, TIMED science discoveries have elucidated the importance of the E-region. Furthermore, the SABER and GUVI instrumentation and retrieval and data analysis methodologies can be adapted to observe and quantitatively advance the understanding of the last frontier in atmospheric research – the E-region.

3. Science Goals and Objectives

There are two overarching goals. This first is to make major advances in quantitatively understanding the physical and chemical mechanisms that govern energy deposition and dissipation, and photochemistry of the E-region. The second goal is to quantify the background neutral and plasma state of the E-region in order to diagnose the dynamical coupling between the lower atmosphere and the IT system, and diagnose the modulating role of equatorial E-region electrodynamics in coupling the F-region to lower atmospheric wave disturbances. These goals will be achieved by answering the following science questions.

Q1: What are the infrared, visible, and UV emissions that are important for understanding the E-region energy deposition, radiative energy dissipation, and photochemistry from 100-200 km?

Q2: What is the thermal structure (neutral temperature and total density) and neutral composition from 100-160 km? The major neutral species are N2, O2, and O while the important minor neutral species are CO2 and NO.

Q3: What are the key plasma concentrations and parameters: NO+, O2+, e, total ionization rate?

Q4: What are the neutral winds from 100-160 km?

These four science questions are sufficient to reach closure on achieving the goals of the E-region science mission.

4. Satellites and Instrumentation

The E-region goals and science objectives can be achieved with two back-to-back polar orbiting satellites in orbits similar to the TIMED satellite, which is s74 degree inclination, sun-synchronous orbit. The leading satellite will contain SABER-like and GUVI-like instruments, but adapted to achieve the E-region mission goals and objectives stated above.

The SABER-like instrument will have twelve broadband radiometer channels: 2x15um, 2x4.3um, 5x5.3um, 1x2.7um, 1x2.0um, and 1x1.27um. The 15um channels will be used to retrieve neutral temperature and pressure in the stratosphere where the local thermodynamic equilibrium (LTE) approximation is valid. Once temperature and pressure are determined in the stratosphere, temperature and CO2 concentration can be retrieved in the non-LTE regime from the mesosphere to about 120 km using the 15 um and 2.7 um channels. This is similar to the SABER approach to retrieving temperature and pressure, except that the optically thin 2.7um channel is used instead of the 4.3 um channel in our new method, which will ensure continuous temperature and density profiles from the tropopause to 120 km for diagnosing wave coupling between atmosphere regions. The short-wave 4.3um channel containing the CO2 emission bands will be used as an additional measurement constraint in the temperature and pressure retrievals. The long-wave 4.3um channel contains most of the NO+ emission bands and will be used to characterize the E-region electron density and infrared auroral energy dissipation. The 2.0um channel contains mesospheric OH emission and is needed to model the CO2 4.3 um emission above 100 km due to non-LTE processes. Five 5.3um channels will be used to extend the temperature retrieval to 160 km while simultaneously retrieving the NO concentration. The 1.27um channel is a diagnostic measurement for understanding ion-neutral chemistry, as discussed above, and may also be used to retrieve atomic oxygen.

The GUVI-like instrument will sample the same atmospheric volume as the SABER-like instrument. The GUVI-like instrument will measure atomic oxygen at 135.6 nm and N2 LBH bands in order to derive the O/N2 column density ratio (referenced to a N2 column density of 10^{17} cm^{-2}) and the total solar EUV energy flux below 45 nm. Atomic hydrogen 121.6 nm measurements will also be included to help distinguish between proton and electron aurora. The NO-gamma band will be observed to retrieve NO concentration during the daytime. A near-infrared spectrometer observing the O2 atmospheric bands will used to retrieve the daytime neutral temperature profile from 100-160 km, as was demonstrated by the new RAIDS sensor suite. This technique will provide a redundancy in E-region neutral temperature data during the daytime. Atomic oxygen red line (630 nm) and green line (557.7 nm) and O2 Herzberg I photometers will be used to fit a Chapman profile to the atomic oxygen density, in combination with the O2 1.27 um and O2 atmospheric band measurements, using inversion techniques advanced by *Haley et al. [2001]*. The N2+ emissions at 427.8 and 391.4 nm will be observed in order to derive precipitating particle energy characteristics and the total ionization rate profile [*Rees and Jones, 1973*].

The trailing satellite will contain a spectral near-infrared instrument and a spectral RAIDS-like instrument. The infrared instrument will be modeled after the highly successful field-widened Michelson Interferometer (FWMI) launched out of Poker Flat on a Sergeant sounding rocket [*Picard et al., 1987; Espy et al., 1988*]. The FWMI was the first to provide high-resolution infrared spectra of atmospheric emissuib as a function of altitude, and was the first instrument to resolve CO lines near 4.7um and to identify NO+ emission in the 4.3um region. This instrument is currently being redeveloped under the Geospace Instrument Development Program and will measure infrared spectra from 1-6um. The RAIDS instrument measures spectral radiance from the near-infrared O2 atmospheric bands through the EUV region, and has been demonstrated on the ISS.

The purpose of the trailing satellite is optical exploration of E-region energetics and chemistry. The FWMI and the RAID-like instruments observe all the spectral fingerprints important for quantitatively advancing a physics-based understanding of the E-region energy deposition and radiative dissipation processes, and the fundamental chemical and ion-neutral coupling mechanisms. All of these processes influence the composition, energy transport, and dynamics of the global IT system. The orbit of the trailing satellite is such that some of the sampled atmospheric volume overlaps the leading satellite sampling volume. Thus, the close time coincidence between the two satellites enables the trailing satellite data analysis to benefit from the leading satellite data products. The temperature, density, and composition data products obtained from the leading satellite can be used as input data in modeling the spectral radiance measurements taken by the trailing satellite. This approach can be used as a consistency check on the leading satellite retrieval methodologies, can lead to the development of improved retrieval methodologies, and provides independent spectral measurements necessary for quantifying the energy transport and chemical processes that govern the neutral and plasma properties of the E-region.

In comparison with data reduction techniques utilized by the TIMED mission, 2-D retrieval will be performed to derive all data products. This will more accurately account for horizontal inhomogeneities along the limb line of sight. In addition, the possibility of employing tomographic techniques in the data reduction will also be explored. The E-region mission concept team contains the expertise required to develop the proposed instruments and to derive the science data products.

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Initiation of Irregularities in the Equatorial F-Region Ionosphere

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Introduction

Plasma irregularities[1] in the low-latitude nighttime equatorial ionosphere are well known to affect geolocation and communication systems that employ trans-ionospheric radio links. Figure 1 illustrates the effect of a GPS signal passing through an equatorial depletion (dark finger structure) observed by an airglow imager in western South America. Figure 2 illustrates the "wedge" geometry of equatorial plasma depletions extending from hemisphere to hemisphere along the geomagnetic field. These three-dimensional maps illustrate the wide area that is affected by depletions.

[1] In this document, the physical terms *irregularity* and *depletion* will be used in lieu of the observational terms *spread F*, *scintillation*, *ionospheric clutter*, *plumes*, and so on. For informal discussion, the reader may freely interchange these terms, although there are subtle differences.

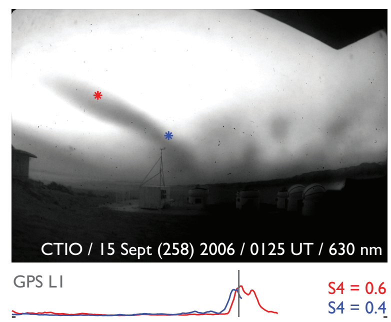

Figure 1: GPS L_1 fading observed coincident to plasma depletions in airglow images over western South America. Image courtesy of Jonathan Makela at the University of Illinois.

The following questions are asked and addressed regarding the initiation of equatorial irregularities: *Is the large-scale wave-structure (LSWS) a necessary precursor for interchange instability growth at the equator? What causes meter-scale backscatter? What is the relationship between the plasma drift and neutral wind at a given location?*

Although this paper is written primarily from a ground-based perspective, the major point is to address space-based ITM observation missions and identify the sensor products most beneficial to addressing the foremost questions in equatorial irregularity research. Space-based instrumentation is an important partner to ground-based instrumentation by providing broad spatial and detailed in situ context of phenomena [e.g., Kelley et al., 2003].

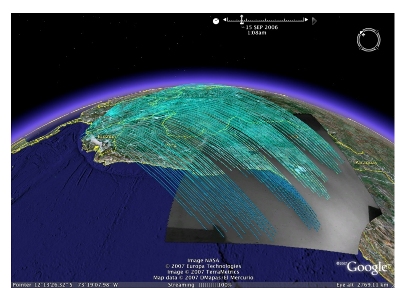

Figure 2: Airglow depletions from the same night as Figure 1 extruded along the geomagnetic field to illustrate three-dimensional "wedge" geometry of depletions.

Seeding of Equatorial Depletions

The principal geophysical process that causes nighttime plasma irregularities in the low-latitude of F region is an interchange (gravitational Rayleigh-Taylor) instability, illustrated in Figure 3. Following sunset at E-region altitudes (around 110 km), the E region recombines rapidly in the absence of ionizing solar FUV radiation. A sharp density gradient remains on the bottom side of the F region. Small perturbations in this interface are amplified through the feedback between a polarization $\mathbf{E}$ field and the $\mathbf{E} \times \mathbf{B}$ drift.

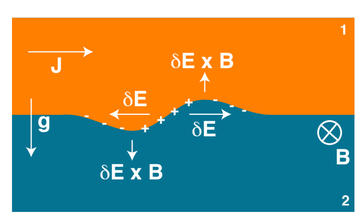

Figure 3: A cartoon of the Rayleigh-Taylor interchange instability showing how small perturbations in bottom side F-region interface become unstable.

The source of these perturbations or the seed has been a long-standing effort in the community but the complexity of proposed drivers and the variability of the ionosphere-thermosphere system make it a challenging problem. Compelling evidence is mounting that the initiation is a cascade or sequence of plasma instabilities. It is theorized that the zonal [Kudeki et al., 2007] and meridional [Mendillo et al., 1992] neutral winds play an important role in the initiation of irregularities. Therefore, it is conceivable that gravity waves, which are a neutral perturbation phenomenon, may modify the background wind in a manner conducive to irregularity development [e.g., Kelley et al., 1981, Nicolls and Kelley, 2005, Tsunoda, 2010, Makela et al., 2010]. Tsunoda [2007] and Miller et al. [2009] have also shown that electric fields associated with off-equator irregularities in the *E* or lower *F* region may be responsible for seeding of certain kinds of irregularities.

Hysell et al. [2004] and Kudeki et al. [2007] have demonstrated that electrodynamics of the evening ionosphere can produce seed instabilities capable of triggering the Rayleigh-Taylor instability under favorable conditions. These irregularities, termed *bottom-type layers* in [Woodman and Hoz, 1976], grow with wavelengths on the scale of 20–30 km. Bottom-type layers are identified in radar backscatter plot in Figure 4. Bottom-type layers often form within a larger structure called the large-scale wave structure, or LSWS [Tsunoda and White, 1981, Hysell et al., 2005]. Although bottom-type layers appear to be a necessary precursor to larger post-sunset irregularities, their presence is not alone sufficient to initiate depletion formation.

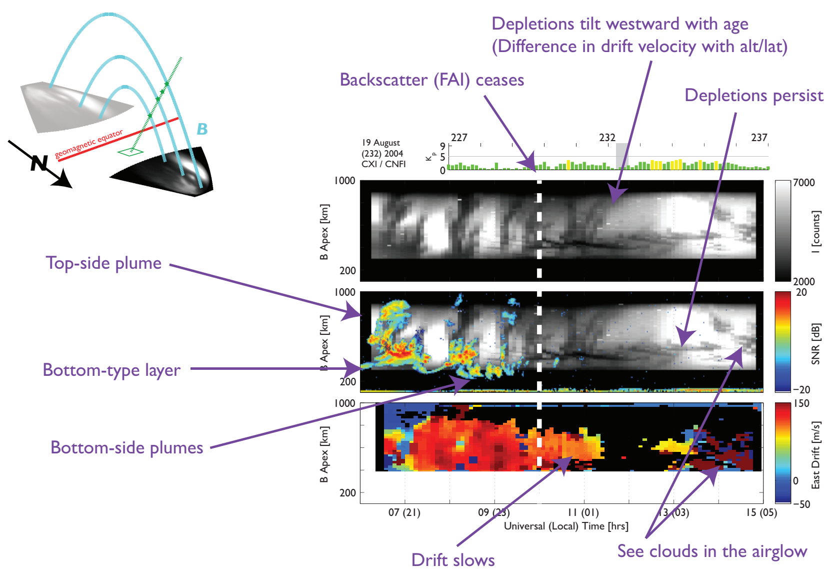

Figure 4: Typical depletion life-cycle during the course of one night as seen from an airglow imager and VHF radar. The inset at upper left illustrates the approximate observation geometries. Radar range gates have been mapped along the geomagnetic field to the airglow layer in order to show the co-location of small-scale field-aligned irregularities that cause radar backscatter and the large-scale depletions. The drifts in the bottom plot panel are zonal eastward drifts derived from the airglow images. Figure based on Miller et al. [2010].

Distribution of Irregularity Scales

It is well-known that at large scales (many 10s of km), secondary irregularities tend to grow on the western wall of the depletion under the influence of an eastward neutral wind [Tsunoda, 1983]. In the rare event of a westward neutral wind, secondary irregularities may grow on the eastern wall [Makela et al., 2006]. There is also substantial evidence that coherent radar backscatter at the meter-scale range occurs from the center of depletions [Tsunoda, 1980, Otsuka et al., 2004]. Furthermore, the km-scale irregularities that cause radio wave scintillation are difficult to locate because scintillation is an effect that results from the combined action of electron density gradient and irregularity scale [Yeh and Liu, 1982]. The presence of meter-scale waves facilitates detection of larger-scale waves and structures such as the bottom-type layers, as well as depletions, following the argument above that they occur principally in the depleted region.

Questions

These questions all relate to the over-arching question: What is the seeding mechanism for equatorial plasma depletions?

Is the LSWS a necessary precursor for interchange instability growth at the equator?

If the LSWS, depicted in Figure 5, is a necessary and sufficient condition, what is its origin? Do the signatures of LSWS appear before sunset?

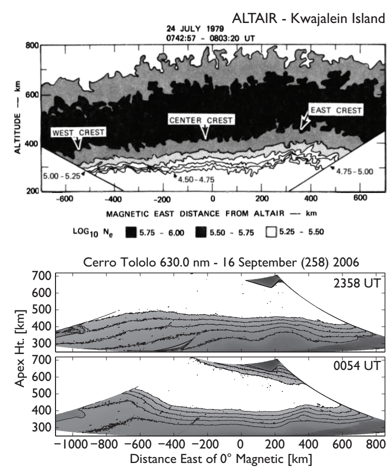

Figure 5: Large-scale wave structure observed by incoherent scatter at ALTAIR (from Tsunoda and White [1981]) and airglow imaging at Cerro Tololo, Chile (after Makela and Miller [2008]). Figures reprinted with permission of AGU.

What causes meter-scale backscatter?

Meter-scale radar backscatter affords the highest spatial and temporal resolution for imaging depletion initiation. What undetected processes before the onset of meter-scale backscatter play an important role in depletion formation? Do instabilities causing scintillation and meter-scale backscatter share a common driver?

What is the relationship between the plasma drift and neutral wind at a given location?

Although this question may be difficult to resolve with spacecraft observations alone at bottom-side F region altitudes of 200–250 km, it is critical to understanding the life-cycle of depletions that occur during the start up of the F-region dynamo at sunset.

Needed Observations

Depletion structure

In situ observations reveal small-scale density variations. However, they are limited to the satellite altitude. Satellite altitudes that are useful for depletion seeding studies are too low for useful satellite lifetime. So, it is sensible to include remote techniques as well. The only presently operational self-contained space-based remote-sensing instruments are radio occultation receivers and optical photometers and imagers. Although radio occultation can estimate the ionospheric profile and scintillation region location, it is incapable of revealing the two- and three-dimensional structure of depletion regions in the same way that an optical imager can, for example this reconstruction from DMSP/SSUSI in Figure 6. Another option may be to develop expendable CubeSats to collect in situ at low altitudes for short lives.

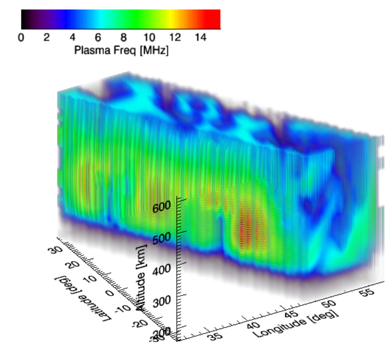

Figure 6: Electron density reconstruction showing three-dimensional depletions from the Special Sensor Ultraviolet Spectrographic Imager (SSUSI) instrument on DMSP/F16. Figure courtesy of Joseph Comberiate.

LSWS detection

To date, observation of the LSWS has not be reported from a completely self-contained space-based sensor that can operate in all longitude sectors. Nadir-looking photometers configured for 630.0 nm and 777.4 nm (or 135.6 nm) in a low-inclination orbit may be considered a useful minimum for this. A pair of photometers can resolve the altitude of the F-region peak at high ($\sim$ 10 km) spatial resolution. Short lifetime CubeSats carrying in situ plasma diagnostic sensors in low-inclination orbits would be another option.

Thermospheric neutral wind

The thermospheric neutral wind is widely-considered to be an important driver of plasma instabilities. The only instrument presently on orbit that is capable of making these measurements globally is the the CINDI (Coupled Ion Neutral Dynamics Investigation) package aboard C/NOFS (Communication/Navigation Outage Forecast System) spacecraft. An optical interferometer operating at the 630.0-nm emission could be a useful alternative.

Ion and electron drift measurements

Although bottom-side in situ drift measurements may be difficult to obtain, orbit-by-orbit drift measurements may be obtained from both in situ plasma density probes and optical observations.

Conclusion

Equatorial irregularities are an important source of uncertainty in mission-critical space-based communication and geo-location systems. Initiation of these irregularities is still not well understood and it is not clear if reliable forecasting will ever be possible. However, understanding the large-scale wave structure and plasma-neutral interactions near the bottom side *F* region will unlock more secrets regarding the initiation of equatorial depletions. The field-of-view of ground-based instruments is limited although they often possess greater spatial and temporal resolution than their space-based counterparts. Both are necessary to complete the picture of what causes equatorial plasma depletions and the associated irregularities.

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Dear Sir or Madam:

I am sending this letter to express my opinion regarding the current and future state of the ground-based solar physics in the U.S. I am an Astronomer at the National Solar Observatory (NSO) and the Program Scientist for the NSO's Synoptic Optical Long-term Investigations of the Sun (SOLIS) project. From 2005-January 2009 I served as the Program Scientist for the Solar and Heliospheric Program (SHP) and Low Cost Access to Space (LCAS) Program at NASA Headquarters. I am also a member of the Solar Physics Division (SPD) Committee of the American Astronomical Society. I believe that this experience gives me unique perspective on issues that I am writing about.

In my opinion, the groundbased solar physics in the US is lacking a comprehensive strategic planning. In short, the existing National facilities are not adequate, and future replacement does not take into account broad aspects of solar research; funding is split between several agencies, which often results in duplication of efforts; funding model for existing University-owned observatories makes it difficult to run these facilities, and it also precludes a wider use of these facilities.

Currently, the National Solar Observatory is the only National facility in the US dedicated to ground-based solar observations in optical and near-infrared wavelengths. It operates solar telescopes in two sites (Sacramento Peak in New Mexico and at Kitt Peak in Arizona). The telescopes on both sites are getting antiquated, and the NSF is funding a construction of a new facility (Advanced Technology Solar Telescope, ATST) as a replacement. Once ATST is commissioned, two existing NSO sites will be closed down. The plan also calls for relocation to a new site of existing SOLIS instrument to continue the NSO's synoptic program; the NSF plans phasing down the Global Oscillations Network - other NSO synoptic program.

These are all good developments (with the exception of GONG funding). However, there are several areas of concern.

The ATST will be a state-of-the-art, world largest (in aperture) solar optical telescope oriented primarily on high-resolution observations. A competition for the observing time will be extremely high. However, this will be the only national facility available to solar physicists in US, and as the result, many researchers will not be able to get the observing time. Imaging if the night-time astronomers had only one groundbased telescope at their disposal! This will be the situation with the solar ground-based astronomy after ATST is commissioned and existing NSO facilities are closed. Furthermore, many research projects may not be suitable for a large-aperture ATST, some projects require smaller aperture telescopes, longer observing time, or greater flexibility in instrumentation configuration than it will be available with ATST. Also, smaller telescopes are indispensible as the test-beds for student-developed instrumentation. Lacking other National facilities, US researchers would have no choice but to go overseas to get their observations. I have already seen cases, when US research groups are requesting funding to directly support operations of foreign groundbased facilities to get data unavailable from the existing US National facilities. On the other hand, there currently exist several

University-owned observatories in this country that could provide observations bridging current NSO - ATST transition period, and supplementing the future ATST observations. For example, one of these observatories is the Big Bear Solar Observatory run by New Jersey Institute of Technology, NJIT. Last year, NJIT had commissioned a new solar telescope (now the world largest solar telescope), which was constructed with partial support from the NSF. Other examples are Mees Solar Observatory (University of Hawaii), San Fernando Solar Observatory (University of California at Northridge), Mauna Loa Solar Observatory (MLSO, run by High Altitude Observatory), Wilcox Solar Observatory (Stanford University), Mt. Wilson Solar Observatory (UCLA) and others. All these facilities (with the exception of MLSO), however, are supported via research grants and some are on the verge of closure because of lack of steady funding. A typical 3-year grants cycle makes it difficult to run an observatory. Also, because of the nature of support, the Universities are unwilling to provide their facilities to other researchers unless the user fees are paid. This is waste of resources; most, if not all instrumentation on these observatories was developed using NSF or NASA funding, but its usage is limited because of lack of operational funding.

Judging from my private conversations with the NSF and NASA Division and Program Directors, it appears that NSF does not feel strongly obligated to prove a long-term support to University-owned facilities, while NASA's position is to limit its support to the space-based operations only. However, providing a steady funding to some University-owned observatories would make them available to other researchers, which will, in essence, extend the network of the National facilities. And there are clear benefits to NASA from the ground-based solar astronomy. For example, the expertise developed in ground-based spectropolarimetric measurements played a pivotal role in designing the instrumentation and the data analysis for Hinode mission. Magnetograms from Michelson Doppler Imager (MDI) on board SOHO spacecraft went through several updates when observations from Mt. Wilson Observatory were used to re-calibrate the entire MDI data set. There is also overlap between NASA-supported instrument development for high altitude balloons and sounding rockets and the high-resolution instrumentation development supported by the NSF. Having a comprehensive strategic plan for solar physics would highlight areas of deficiency and would also help in reducing duplicate efforts. It would also allow for better coordination between efforts supported by different agencies.

A combination of ground-based and space-borne observations would also be beneficial to such research fields as Space Weather, when ground-based instruments can provide supplemental, calibration, and backup space-weather related data in between NASA missions or at the event of failure of the space-borne instruments.

Having observational facilities with medium and small size telescopes will also be beneficial for education and training of future scientists and engineers by providing a test-bed platform for small Universities' and students' instrument projects. One possible solution could be to identify the most valuable University-owned solar observatories and provide some long-term operation funding for them at the exchange for observing time to scientist from US research community. Alternatively, one could establish a dedicated funding to cover users-fees for US researchers for observing time granted at these University-owned observatories.

Thus, I strongly believe that having a comprehensive long-term plan for ground-based solar astronomy in US is necessary at this time to prevent future shortcomings in this research field.

Sincerely,

Alexei Pevtsov
--

Sounding Rockets as Indispensible Research Platforms for Heliophysics Research

And Development of a High Altitude Sounding Rocket

A White Paper for Consideration by the

Heliophysics Decadal Study Committee

National Research Council

Washington, D.C.

By

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NASA/Goddard Space Flight Center

Greenbelt, MD 20771

12 November 2010

Summary. One of the most robust, versatile, and cost-effective flight programs at NASA, for over 50 years the Sounding Rocket Program has provided critical scientific, technical, and educational contributions to the nation's space program. This white paper first provides an overview of the rocket program's capabilities that are critical for Heliophysics Research. It then describes the very exciting High Altitude Sounding Rocket (HASR) initiative developed at the Wallops Flight Facility and discusses the great promise of this platform for scientific research.

Background. Sounding rockets carry scientific instruments into space along parabolic trajectories, providing nearly vertical traversals along their upleg and downleg, while appearing to "hover" near their apogee location. Whereas the overall time in space is brief (typically 5-20 minutes), for a well-placed scientific experiment launched into a geophysical phenomena of interest, the short time and low vehicle speeds are more than adequate (in some cases they are ideal) to carry out a successful scientific experiment. Furthermore, there are some important regions of space that are too low to be sampled by satellites (i.e., the lower ionosphere/thermosphere and mesosphere below 120 km altitude) and thus sounding rockets provide the only platforms that can carry out direct *in-situ* measurements in these regions. Astronomy, solar, and planetary science missions include sophisticated telescopes with optional joy-stick operated, sub-arc-second pointing for >5 minute continuous observations of astronomical objects, including those too close to the sun for Hubble or EUVE observations. Microgravity missions are carried out on high altitude, free-fall parabolic trajectories which provide ideal microgravity environments without the vibrations frequently encountered on human-tendered platforms.

Low-cost Access to Space. Because the science payload does not go into orbit, sounding rocket missions do not need expensive boosters or extended telemetry and tracking coverage. As a result, mission costs are substantially less than those required for orbiter missions. Furthermore, because the program is managed and the payloads are built in one central location (e.g., the NASA/Wallops Flight Facility), significant savings are realized through efficient, cost-savings operations that procures parts and rocket motors in large quantities and utilizes past designs of sub-systems for follow-on missions. In other words, the sounding rocket program takes advantage of a high degree of commonality and heritage of rockets, payloads, and sub-systems flown repeatedly. In many cases, only the experiment -- provided by the scientist -- is changed. Costs are also very low because of the acceptance of a higher degree of risk in the mission (compared to orbital missions), although safety is never compromised. In some cases (such as almost all astronomy, planetary, solar, and microgravity missions), the payloads are recovered which means the costs of the experiment and sub-systems are spread out over many missions.

Rapid, quick-turn-around. Not only are sounding rocket missions carried out at very low cost, but also the payload can be developed in a very short time frame -- sometimes as quickly as 3 months! This rapid response enables scientists to react quickly to new phenomena (such as observing the Shoemaker-Levy comet impact to Jupiter) and to incorporate the latest, most up-to-date technology in their experiments.

Validating New Instruments and Developing New Technology. The sounding rocket program continues to serve as a low-cost testbed for new scientific techniques, scientific instrumentation, and spacecraft technology, eventually flown on numerous satellite missions. For example, COBE, CGRO, EVUE, FAST, ASTRO-2, UARS, SOHO, TRACE, and numerous other recent NASA Satellite missions have been enabled by technology and techniques developed in the suborbital program. Furthermore, the low cost of sounding rocket access to space fosters innovation: instruments and/or technologies which are not sufficiently developed to warrant the investment of satellite-program scale funding are often "proto-typed" with initial space testing on sounding rockets.

Education. In addition to science and technology, sounding rockets also provide invaluable tools for education and training. For example, a three-year sounding rocket mission at a university provides an excellent research opportunity for a Ph.D. dissertation, in which the student carries the project through all of its stages -- from conception to hardware design to flight to data analysis and, finally to the publication of the results. This "hands on" approach provides the student with invaluable experience of understanding the space flight mission as a whole. Indeed, over 350 Ph.D.'s have been awarded as part of NASA's sounding rocket program.

Unique Features of Sounding Rockets

• Quick, low cost access to high altitudes where optical observations of astronomical, solar, and planetary sources can be made of radiation at wavelengths absorbed by the Earth's lower atmosphere.

• Direct access to the Earth's mesosphere and lower thermosphere (40 - 120 km).

• Low cost.

• Rapid response times.

• Ability to fly relatively large payload (>500 kg) masses on inexpensive vehicles.

• Provision of several minutes of ideal, "vibration-free" microgravity.

• Ability to use the Earth's limb as an occulting disk to observe astronomical sources close to the Sun.

• Ability to gather *in-situ* data in specific geophysical targets such as the aurora, the cusp, the equatorial electrojet, noctilucent clouds, thunderstorms, etc.

• Access to remote geophysical sites and southern hemisphere astronomical objects.

• Long dwell times at apogee.

• Slow vehicle speed with respect to the ambient medium (and much slower than that of orbiting satellites).

• Collection of vertical profiles of geophysical parameters.

• Ability to fly simultaneous rockets along different trajectories (e.g., with different apogees, flight azimuths).

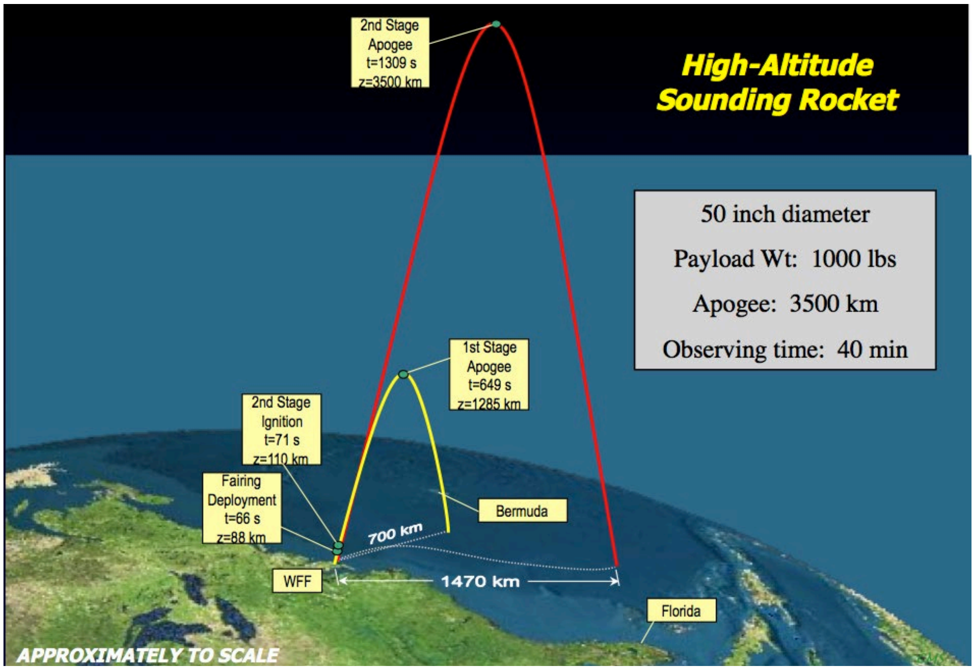
• Ability to fly numerous free-flying sub-payloads from a single launch vehicle.

• Ability to recover and refly instruments.

High Altitude Sounding Rocket

Approximately 8 years ago in 2002, the NASA Wallops Flight Facility developed a prototype design for a High Altitude Sounding Rocket (HASR) whose features are discussed below. When implemented, the HASR will profoundly advance future rocket-based investigations across all scientific disciplines, including X-ray and UV astronomy, planetary science, space physics, and micro-gravity. Furthermore, this new vehicle presents a unique and inexpensive engineering test bed for high velocity landing and aerobraking systems, such as currently being considered for probes that will impact on other planets and return samples to the earth. We believe that the HASR should be the highest priority new technology development for the program.

As shown in the accompanying figure, the preliminary performance requirements for an HASR are that it achieve an altitude of 3000 km, provide ~2400 seconds of observing time above 100 km, and include the option to be recoverable. In addition, the preliminary HASR configurations presented thus far have 38" (~1meter) diameter experiment sections, significantly larger than current payload diameters (17" and 22"). As typical astronomy/planetary/solar BBIX payloads



currently achieve approximately 240 seconds of actual observing time above the atmosphere, the HASR would provide an order of magnitude more observing time. Since the larger diameter rocket payload would provide an additional 3 to 6 times more geometric collecting area, the combination of these factors would provide 10 to 60 times more sensitivity for telescope instruments than is typically afforded with the current rocket technology.

In addition to payloads that seek primarily to increase observing time above the atmosphere, a high altitude sounding rocket would also be very advantageous to Space Physics investigations of Geospace. For example, such a high altitude rocket would penetrate the prime auroral and cusp acceleration regions (> 2500 km) where they would gather high resolution particle and fields measurements at a very slow velocity compared to orbiting satellites. The payload would be able to stay within the region of interest on time scales that would permit longer period phenomena, e.g., pulsations, to be resolved, which is not possible with in-situ probes on low earth orbiting satellites, such as FAST, that traverse such regions in a few minutes. In addition to auroral studies, such missions would also provide new investigations of the inner radiation belts and other space physics phenomena. The larger diameter payload would permit more extensive sub-payloads to be developed for multi-point sampling of a variety of regions of geophysical interest.

In the realm of engineering, the new vehicle promises to be highly beneficial for the testing of new scientific instrumentation, such as that proposed for orbiting satellites at low perigee, as well as the testing of smart landers and aerobraking systems. The ability to test planetary re-entry engineering devices opens a new area for research within NASA's sounding rocket program.

The HASR promises to be highly cost effective. For example, a typical BBIX astronomy sounding rocket mission costs approximately $1.5M and provides approximately 6 minutes of observing time. In contrast, the HASR system is projected to cost $5M but would provide 40 minutes of observations. Thus, in addition to the new experiments that are afforded by such a longer duration, high altitude platform, the combined increase in observing time with the relatively low cost vehicle would decrease the cost of observations per minute by a factor of two.

Finally, we emphasize that throughout the history of scientific exploration, major breakthroughs have traditionally occurred whenever instrument performance metrics have significantly increased. The development of the HASR represents just such an opportunity for NASA and the scientific community. The HASR is the next logical step for NASA's Sounding Rocket Program to take, not only for the immediate advances that it will achieve in scientific research, but also for the development of the next generation of instruments for future satellite missions.

High-resolution, high-accuracy plasma, electric, and magnetic field measurements for discovery of kinetic plasma structures and processes in the evolving solar wind

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To discover and understand the mechanisms responsible for the heating and acceleration of the solar wind is an important goal of solar and space physics that has stimulated scientific study for many years. Although significant progress has occurred in the last few decades, to achieve this goal requires the ground truth provided by an advanced generation of in situ spacecraft measurements. To solve the mystery of solar wind heating and acceleration requires direct observational knowledge of the solar wind structures, plasma waves, and wave-particle interactions that play a dominant role in these processes. Since the relevant mechanisms operate at kinetic scales, it is clear that high accuracy, high cadence plasma and wave measurements are essential to pave the way for the science that will eventually solve this mystery. Progress toward a solution of this fundamental issue requires that these next generation measurements be performed in the inner heliosphere and at 1 AU in the coming decades. Such measurements will also benefit studies of related physical processes such as shocks, including microstructure, and the acceleration of particles from thermal to suprathermal energies leading to the formation of suprathermal tails.

Next generation measurements

To advance knowledge of plasma physical processes in the solar wind at 1 AU and throughout the inner heliosphere there is an urgent need for accurate high cadence particle and electromagnetic field measurements that can resolve scales from 10^{-4} Hz to 20 Hz. Such measurements will enable the discovery, analysis, and understanding of a broad range of kinetic processes including plasma heating processes, current sheet dynamics, small scale magnetic reconnection events, and the processes responsible for dissipation of MHD fluctuations in the solar wind. It is essential to resolve and characterize plasma processes throughout the important transition to kinetic scales that occurs near the proton inertial length and proton gyroradius in order to solve the challenging problem of solar wind heating and acceleration. At 1 AU the proton inertial length and proton gyroradius are typically on the order of 100 km and structures of that size are swept past the spacecraft in approximately 0.2 seconds.

At present, studies of these important processes are hampered by several factors. The plasma density, bulk velocity vector, and particle distribution functions in the solar wind are usually measured with a cadence much longer than 1 second and almost never with a cadence shorter than 1 second. Therefore, existing measurements are unable to resolve plasma structures and processes that operate on scales near the proton inertial length and the proton gyroradius. Solar wind magnetic field data typically cover frequencies that are either less than a few Hz or much greater than a few Hz leaving a gap in our knowledge at the crucial point where there is a transition from MHD scales to kinetic scales, e.g., fluxgate magnetometer data is usually limited to frequencies below a few Hz and search coil magnetometer data to frequencies greater than 10 Hz so that the range around 1 Hz to 20 Hz is often poorly resolved. Electric field measurements in the range of frequencies near 1 Hz are difficult to perform either because of interference from the spacecraft spin (due to photoelectric variations of the antenna potentials), because the electric antennas are too short compared to the Debye length, or for other reasons [Kellogg, 2008]. This is a major drawback since electric field measurements in this range are essential for characterizing the waves and processes near the transition to kinetic scales where kinetic processes begin to dominate the physics. Consequently, solar wind structures, dynamics, and plasma processes at scales from seconds to milliseconds are poorly understood and largely unexplored at present.

To open up this unexplored territory and to advance plasma physics and solar wind science, the development and implementation of instrumentation for sustained, simultaneous, accurate, high cadence plasma particle, electric field, and magnetic field measurements are required. Specifically, continuous coverage in the range from 10^{-4} Hz to 20 Hz is needed. The critical measurement quantities are the electric field vector, the magnetic field vector, the proton number density, proton temperature, and the proton bulk velocity vector. The number density, temperature, and bulk velocity vector of alpha particles and electrons are also desirable but not essential. In addition, full proton distribution functions (DF) with a reduced cadence (e.g., 30 seconds) are needed for the diagnosis of kinetic processes; the time interval used to measure the DF could be the same time interval used to compute the moments or a somewhat longer time interval to obtain better statistics. Higher frequency measurements of vector electric and magnetic fields in the range from 1 Hz to 300 Hz are also needed, at least in burst mode, to allow investigation of kinetic processes at electron scales. A search coil magnetometer similar to the one on board the *Cluster* spacecraft but with higher sensitivity is needed to provide the required high frequency magnetic field measurements [Cornilleau-Wehrlin et al. 2003].

In the range $\leq$20 Hz, an important goal is to improve measurement accuracy by roughly an order of magnitude over existing measurements since higher frequencies are usually associated with smaller changes in the physical variables. Magnetometer measurements at frequencies up to a few Hz have an absolute accuracy of approximately 0.1 nT [Lepping et al. 1995; Acuna et al. 2008], limited by the spacecraft field. The goal for the next generation of instrumentation, for fluxgates or other designs, is to improve the accuracy by a factor of between 3 and 10 to obtain an accuracy <0.033 nT for each orthogonal component—ideally, the desired accuracy is <0.01 nT—and to reduce interference from spacecraft fields so as to achieve solar wind measurements with this improved accuracy.

Measurements of proton bulk velocity obtained using, for example, the Faraday cups on board the *Wind* spacecraft, have achieved an uncertainty as low as 0.16% in magnitude (~1 km/s) and 3° in direction [Kasper et al. 2006]. Previous solar wind measurements have achieved an accuracy of 1.5° in direction [Feldman et al. 1977]. The proton density is generally not measured very accurately and its calibration varies with bulk speed and temperature [Petrinec and Russell, 1993]. The goal for the next generation instrumentation is to improve the accuracy by a factor of between 3 and 10 for the proton speed, direction, and density at a cadence up to 20 Hz—20 Hz desired—with similar order of magnitude improvements for the proton temperature. This can be accomplished through marginal or modest increases in various design factors such as collecting area, number of sensors simultaneously deployed, power consumption, etc.

Three axis electric field measurements with an uncertainty <3 μV/m for each orthogonal component provide the desired improvement over existing measurements at 20 Hz, however, interference from the spacecraft must also be minimized to allow accurate solar wind measurements at these levels. All of the abovementioned requirements will stretch the limits of existing instrument techniques and spacecraft technologies, but are achievable without the development of new measurement techniques, electronic components, or capabilities.

Some Key Science Questions

Current sheets and magnetic reconnection. It is known that the solar wind contains magnetic discontinuities (current sheets) of all amplitudes and thicknesses [Siscoe et al., 1968; Vasquez et al., 2007; Neugebauer and Giacalone 2010] and that the frequency of occurrence of these structures increases as the amplitude decreases. The discontinuities could be long-lived fossils from the Sun [Burlaga, 1969; Borovsky, 2008], long-lived structures generated by processes in the solar wind [Vasquez and Hollweg, 1999; Parker, 2004], or short-lived current sheets forming in the wind [Greco et al., 2008]. Computer simulations show that under the action of compression or expansion, a current sheet in a plasma will form distinct substructure [Schindler and Hesse, 2008]. Diagnosis of this fine-scale structure may provide information about the age and history of the current sheets. Why are some discontinuities diamagnetic [Burlaga, 1968] while others are not? High-time-resolution density, temperature, and anisotropy measurements are required to characterize the internal plasma of the current sheet and find hints as to the physical mechanisms that have produced them. Computer simulations indicate that MHD turbulence will produce thin current sheets at the turbulence dissipation scale [Dmitruk et al., 1998; Maron and Goldreich, 2001], which is the ion inertial length or ion gyroradius. Reconnection at these fine-scale current sheets could be a major dissipation mechanism for the turbulence and for the heating of the solar-wind plasma [Servido et al., 2010]. Reconnection exhausts have been identified in 3 s solar wind plasma and magnetic field data down to spatial scales of 25 ion inertial lengths and there are indications in 0.1 s magnetic field observations that many smaller reconnection exhausts are yet unresolved by present plasma measurements [Gosling and Szabo, 2008]. High-resolution high-accuracy measurements are required to see these current sheets and to determine how often they undergo reconnection. Some key questions: What are the characteristics and frequency of occurrence of magnetic discontinuities and current sheets in the solar wind at scales near the proton inertial length and proton gyroradius? Is fast reconnection taking place at these scales and, if so, then what role does this process play in the heating of solar wind plasma and the dissipation of MHD turbulence?

Dissipation of MHD turbulence and plasma heating. Solar wind fluctuations generate a turbulent energy cascade from large to small scales and the dissipation of this energy cascade is believed to be a primary source of heating of solar wind plasma at heliocentric distances below 5 AU or so [Matthaeus et al. 1999; Smith et al. 2001]. This process is also believed to be a viable mechanism for the heating of the solar corona [Cranmer et al. 2007; Verdini et al. 2010]. However, the physics of the dissipation process in collisionless space plasmas is not understood. Theory and simulations suggest that the predominantly

Alfvenic fluctuations at MHD scales have wavevectors oriented obliquely to B_0 and that this Alfven wave cascade excites a kinetic Alfven wave cascade (KAW cascade) at the proton gyroradius scale which dissipates and heats the plasma through Landau damping and possibly other mechanisms [Howes et al. 2008; Schekochihin et al. 2009]. Tentative evidence for such a KAW cascade in the solar wind has been obtained by Bale et al. [2005] and by Sahraoui et al. [2009, 2010]. Nonlinear processes are expected to be important because wave amplitudes at the proton gyroscale are not negligible, with $\delta B/B_0 \sim 5\% - 50\%$ [Lau & Siregar 1996, Markovskii et al. 2008]. However, the details of these nonlinear mechanisms are unknown. To elucidate the physics of turbulent dissipation and plasma heating in the solar wind requires high cadence plasma and field measurements capable of resolving proton and ion kinetic scales. Among the key science questions: Are kinetic Alfven waves the dominant wave modes at proton kinetic scales and what other wave modes are present, if any? What is the wavevector spectrum of the different wave modes? What is the relationship, if any, between the observed waves and plasma structures such as current sheets? How do ions and electrons interact with the observed wave fields and what are the principle wave-particle interactions or other mechanisms responsible for plasma heating?

Recently it has been shown how the energy cascade rate of MHD turbulence in the solar wind can be determined using in situ measurements [MacBride et al. 2008]. Measurement of the energy cascade rate in the solar wind is experimentally challenging because it requires large amounts of data acquired under relatively steady and homogeneous conditions. Measurement techniques based on the Politano and Pouquet relations are now well established. However, existing measurements have uncertainties that may be on the order of 100% [Podesta et al. 2009; Podesta, 2010]. High cadence solar wind plasma and magnetic field measurements are needed to make practically useful measurements with uncertainties less than 20% or 30%. Accurate measurements of the energy cascade rate are crucial for assessing the role of turbulent dissipation in solar wind heating. Some key questions are: What is the energy cascade rate of MHD turbulence in the solar wind? How does the energy cascade rate (the heating rate) depend on the normalized cross-helicity of the fluctuations and how does the cross-helicity behave at the transition to proton kinetic scales? What is the nature of the anisotropy of the fluctuations in the kinetic range of scales and what role does this anisotropy play in the turbulent heating of the plasma?

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Research to Operations (Res2Ops)
Opportunities for Center Development

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The transition from scientific research into operational tools has been difficult to accomplish in many areas in space physics. Part of the problem stems from the fact that space physics tends to be discovery driven, whereas the development of new operational tools requires technical integration of many already developed methods, techniques and ideas. A minimally successful operational tool must be well-tested, utilize rigorous, well-documented mathematical or technical approaches, and efficiently generate results over a wide range of input parameters. A scientific model can become particularly valuable as a prospective operational tool when its predictions often agree with a variety of observations under a wide range of circumstances within stated margins of uncertainty. To do so it also must target areas where a substantial user-community greatly benefits from the tool's existence, functionality, robustness and accuracy. Thus, the development of highly successful operational tools must fill a demonstrated or emerging need and combine best practices in engineering, physics, computer science, and management.

The fact that there are so many requirements on successful tool development in the vast area between research and operations explains why tool development is costly and cumbersome. A successful research-to-operations team must be broad, combining outstanding programmers, scientists, and engineers. This required breadth lends itself naturally to the formation of a number of research-to-operations Centers at Universities and Labs throughout the country. In this way, they can at the same time contribute substantially to training future specialists who will be needed in the user community. To be sustainable though, such centers need to be able to compete for a predictable funding resource, which in some areas tends to fall between the competencies of different funding agencies.

A given research-to-operations Center focuses on a specific technical topic (e.g., radiation in space, ionospheric response, etc) and gathers input from the scientific community in the form of theories, algorithms, models, validation techniques, and data to develop specific deliverables (e.g., space radiation forecasts on 1-hour, 1-day, 1-week timescales). A research-to-operations Center has a governing board that provides feedback about tool usability, accuracy, relevance, and robustness. The governing board is composed of knowledgeable scientists, model developers, theoreticians, experimentalists, and members of its user-community.

A single individual (a scientist or engineer) manages a research-to-operations Center and assumes overall responsibility for tool development. The approach suggested here in which a Research-to-Operations Center has a singular focus, is centrally lead, and has feedback from a governing board will allow many areas in space physics to develop more highly functional tools that become greater resources to targeted user-communities.

NESSC Summer School for Undergraduates in Space Physics

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Abstract: The New England Space Science Consortium (NESSC) can provide both governance and lecturers in a new one or two week summer school for undergraduate students interested in continuing in a space science career. This summer school provides students with an intellectual background to help in the pursuit of research projects in REU and graduate programs in space physics.

The New England Space Science Consortium

The NESSC creates a cross-disciplinary, multi-institutional forum to address cutting edge research topics with a broad view toward collaboration on major opportunities in solar and space science. See http://nessc.unh.edu/ for a detailed overview of NESSC activities since 2005. The consortium brings together researchers and students at the University of New Hampshire (UNH), Boston University (BU), the Harvard-Smithsonian Center for Astrophysics (CfA), MIT, the Air Force Research Laboratory (AFRL) at Hanscom AFB, Dartmouth College, the Haystack Observatory, Tufts University, and other organizations.

➢ *The NESSC seeks to initiate a one or two-week summer school for students throughout the country who are considering careers in space science.*

The consortium is a grass roots organization founded by Nathan Schwadron, Charles Smith, Harlan Spence and Eberhard Moebius (University of New Hampshire), Nancy Crooker (Boston University), John Raymond and Justin Kasper (CfA/SAO), and Mary Hudson (Dartmouth College). The group meets at informal meetings in which highly relevant, interdisciplinary research topics are presented and discussed. The consortium's broad scope has, thus far, engaged researchers from the solar, heliospheric, solar wind, magnetospheric and ionospheric communities. Continued growth in the consortium's scientific breadth and depth will be encouraged.

There are a number of notable examples of interdisciplinary areas that have or will be pursued by the consortium:

- There is considerable interest in a new direction that our field is taking toward establishing plasma physics of the local cosmos as a basic science. Physical processes such as magnetic reconnection, turbulence, and plasma-neutral coupling occur in diverse astrophysical settings, including accretion disks surrounding compact objects such as neutron stars and black holes, shocks surrounding supernovae and gamma ray bursts, and superheated plasmas within globular clusters and the intergalactic medium. There is significant potential for the generalization or "universalization" of such processes. Given recent progress and interest, magnetic reconnection has been the focus of much discussion. Magnetic reconnection is critical for changing global magnetic topologies in the solar corona and magnetosphere and is responsible for transferring stored magnetic energy into plasmas, causing heating and perhaps explosive events like flares. This research complements new laboratory reconnection experiments and aids in our understanding of exotic processes such as angular momentum transport in accretion disks.

- There are inherent connections between space science and astrophysics. Energetic particles and cosmic rays are accelerated within our solar system and the heliosphere in much the same way as they are throughout the galaxy (for instance, at supernova shocks, thought to be the dominant source of galactic cosmic rays with energies below 10^{14} eV). Similarly, our Sun is our nearest star and understanding its physics is a starting point for understanding stars throughout the galaxy and the universe. Understanding our heliosphere and its interaction with the interstellar medium is a starting point for understanding the "astrospheres" around other stars. These examples of the connections between space physics and astrophysics are by no means exhaustive. Such examples become increasingly relevant as our physical understanding of these systems becomes more detailed and as we inexorably develop more sophisticated observational techniques. Indeed, it is through the development of a more accurate and detailed physical picture that we begin to understand our vast and inherently connected universe.
- Our Sun is highly dynamic on timescales of billions of years down to seconds. Its vast magnetic re-organization, which occurs continuously and cyclically (e.g., over the 11- year solar cycle), leads to the periodic release of large eruptive events called Coronal Mass Ejections (CMEs). CMEs occur most frequently near solar maximum. These events can carry strong magnetic fields and can cause strong shocks to form in the interplanetary medium. The strong fields and shocks, in turn, disrupt Earth's magnetosphere and the atmospheres and/or magnetospheres of planets throughout the solar system. The CME shocks also accelerate high-energy particle radiation that is extremely dangerous to astronauts. CMEs, shocks and energetic particle radiation are all forms of "space weather", which we are learning more about by the day. We want to know how to predict space weather to protect our growing space-based infrastructure and future explorers that will venture to the Moon and beyond as a part of NASA's vision for space exploration. We want to understand the implications and connections of space weather to our planet, its electrodynamic environment, its weather, and its evolution.

In all of these areas, an intellectual dialogue that cuts across the traditional boundaries of space science is essential. In this respect, the New England area is fortunate to have such diverse research groups in space science that can come together in an interdisciplinary, multi-institutional forum and bring their collective resources to bear on critical topics. The format for discussion in the New England Space Science Meetings has evolved and will continue to do so. Recent meetings often involve one or two multi-hour discussions of fundamental physical processes with illustrations drawn from the vast range of space science disciplines. When structured around a shared lunch with time for private discussion, this format provides a friendly atmosphere where colleagues can become more familiar with one another, forge new collaborations, raise questions, and share information and insights. The forum also presents a unique opportunity to provide students with a broad view of the field of space science. It is anticipated that one or more half-day or full-day workshops will continue to be convened annually.

- *The summer school in space science will build on the diverse expertise represented by the NESSC, reaching out to others in the community as needed, to provide a unique and advanced educational experience for motivated undergraduates interested in pursuing a career in space science.*

Pedagogical Philosophy of the NESSC Summer School

The transition from an education in physical sciences to research in space physics can be rough. Students often find it difficult to relate their understanding of basic physical processes to the open questions of space physics. There is also a lack of education of basic research tools such as IDL, which can greatly facilitate student engagement in research programs. The NESSC Summer School seeks to expose students to cutting edge topics of space physics, and to relate these topics to the basic pedagogy used in undergraduate education in the physical sciences. The NESSC Summer School seeks to make solar and space physics more accessible to students by explaining how space physical processes are based on fundamental physical laws. Lectures, hands-on exercises and activities will explore what we know about space physical processes, where controversies exist, and how new research may help to untangle these controversies. By-products of the Summer School include modular educational segments that may be used as a part of one or several ~50 minute lectures (lecture material, activities, problem sets, exercises and labs) in classes on Electricity and Magnetism, Classical Mechanics, Statistical Mechanics, Quantum Mechanics, etc. The NESSC Summer School provides a foundational platform for undergraduate students to engage in Space Physics research by developing technical skills critical for performing research, providing connections between theories and models, and providing a broad background for a physical understanding of the Sun, and its broad effects on Earth on the planets and on the heliosphere as a whole.

Overview of the Space Physics Summer School

The models for this summer school are the UofAz/NSO summer school in solar physics previously run at the NSO facility and the Heliophysics summer school run in Boulder. Each of these two programs were/are geared toward graduate students and beginning postdoctoral scientists. The Boulder program explicitly calls for applications from advanced graduate students and recent PhDs. Our program will begin with basic discussions needed to understand the topic, and evolve the topic over the course of the week covering fundamentals in the subject until the cutting edge of research is reached and explored. In so doing, we intend to provide a formal and thorough grounding in a subject critical to space physics research today and in the future. Each year the summer school's governing board will determine a range of topics that spans the connected system from the Sun to Earth, through the solar system and heliosphere. The program is intended to challenge students and demands only those who are serious and dedicated.

- *Space physics is rarely taught at the undergraduate level and students who might otherwise consider a career in the subject are not exposed to ideas, the subject, or the techniques. We believe that by teaching advanced topics of scientific research from* *the solar and space physics discipline, we can create a vehicle that exposes students to the general field as well as the exciting research within the field and thereby capture future scientists who might otherwise select a different career path for want of exposure.*

One small part of the inspiration behind the NESSC summer school comes from the fact that we have sent motivated undergraduates to the NSO summer school when it was possible. Because the NSO summer school was very advanced by undergraduate standards, we chose only students who already had research experience and who had already attended the space science seminars offered within the department. Those students flourished and returned stronger and more motivated, inspired, and with a degree of seriousness and personal responsibility for their research efforts that eclipsed anything they had shown before. We want to offer that same opportunity to a greater number of motivated students in a forum tailored to their needs and background.

Each summer school will focus a well-determined and balanced set of research topics encompassing magnetic reconnection, particle acceleration, turbulence, plasma-neutral coupling, plasma boundaries such as the magnetosphere and heliosphere, etc. Summer schools will incorporate material focused on physical processes and then relate these physical processes to the interconnected systems that couple the Sun, Earth, planets and the heliosphere. Therefore, space physical processes form an intellectual glue that connect subdisciplines such as magnetospheric physics, solar physics, ionospheric physics, and heliospheric physics.

- *We will open the summer school to high school science. At least in the state of New Hampshire, a H.S. science teacher has a B.S. in science with a teaching certificate, so they come to the program equally well trained as many college undergraduates. The primary goal is that they will become better informed on space science morphological issues such as general solar and magnetospheric structure and bring that information back to high school education with the eventual goal of providing teaching materials and lesson plans for other high school science teachers.*

We will create a governing board to provide direction for future summer schools and select the lecturers in the program. There will be at least one board member from each of the participating schools (Boston College, Boston University, Dartmouth, Harvard-Smithsonian, MIT, UNH, SwRI, JPL, and the Haystack Observatory). Membership may rotate as those who have served give way to others with new energy and new ideas. The organization for the summer school is coordinated by Charles Smith, Nathan Schwadron, Amitava Bhattacharjee, Charlie Farrugia and Harlan Spence at UNH, Josh Semeter and George Siscoe at BU, Ed DeLuca and John Raymond at Harvard/SAO, Emily CoBabe-Amman, Phil Chamberlain, and Hillarie Davis.

<u>Evolution and exploration of new ideas</u> are the key defining principles in the operation of this program. For instance, we do not now intend to write a book as has been so very well accomplished by the Boulder school, but future activities will be determined by the membership and volunteers within the program. Lecture materials will be made available

via the World Wide Web and this will form the beginning of any education-related efforts by this program.

- *We will incorporate carefully chosen high school physics teachers into the program. Their selection may change yearly, or may remain a fixture of the program depending on how well they serve the needs of the program. Their purpose will be to develop new material for high school physics education that exposes younger students to the field of space science.*

The NESSC forms the foundation on which this program will be built. Lecturers will be drawn from the participating schools and programs throughout the NESSC and additional lecturers will be recruited from outside the New England area as needed.

Space Physics Summer School Philosophy

It is important for the reader to understand the nature of this effort. The NESSC was formed in recognition of the potential for broad collaboration by a large number of space science researchers within the New England area. The NESSC has come to represent a successful and well-supported grass roots effort that brings together between 25 and 40 scientists once each semester for a day of scientific presentation and debate. Meetings take on a broad range of formats and topics, but the recent two years have focused on reconnection as a topic of broad interest that spans the solar, solar wind, and magnetosphere research efforts of the members.

<u>We will build on this existing vehicle of collaboration</u>. Initially, we expect to draw the bulk of our students from the New England area only because they represent the schools and faculty who support the program and we feel confident that a suitable number of appropriate students can be found from within these schools. **There is no intent or desire to limit application to this program to New England schools alone.** We note only that the local schools can guarantee success with initial student applications. UNH students who will be already living and working in Durham will provide an additional pool of students requiring no additional funding from this proposal. We will advertise nationally and internationally seeking enrollment from the best and the brightest.

<u>New England has a proud tradition of small, liberal arts colleges</u> that produce excellent students. However, like many schools, these colleges tend to hire astronomers to teach extra-terrestrial physics and their faculty often don't know what constitutes the space physics discipline. UNH has some experience hiring these students for summer research and they are generally quite good, very bright, and handle responsibility well. We propose to actively recruit from these colleges in the hope that the students will take back to their home schools an improved knowledge of space science and thereby act as ambassadors for space science to their home institutions.

<u>We would propose that the summer school never be viewed as a closed-door event</u>. While there will be formally enrolled students (those needing support to live locally and those from the host school who can attend without support) we would hope that as the

subject is evolved to more advanced levels late in the week, older students (graduate students, postdocs, and mature researchers) will desire to sit in and listen to the more advanced lectures. This can only enhance the overall experience of the students so long as lecturers remember the identity of their prime audience.

Curriculum development for an undergraduate audience requires coordination by the teaching faculty. Getting researchers to cooperate as part of a unified program, recognizing the need for an orderly development of the subject and a consistent use of notation is notoriously difficult. Nonetheless, it is required and will be supported by the governing board.

Space Physics Summer School Curriculum

The stated goal of the summer school will be to provide both fundamental education in space physics .We recognize that undergraduates (the primary target of this effort) are ill-equipped to understand advanced topics such as magnetic reconnection, particle acceleration, etc. Therefore, the first part of every school must be spent in developing the basic tools needed to understand the new science. For instance, the first lectures in the reconnection school will be an extensive discussion of Maxwell's equations and the development of magnetohydrodynamics. From these fundamentals we will build a case requiring reconnection as a fundamental process and only after this will begin to explore how magnetic reconnection is utilized to understand subdisciplines in space physics. By teaching reconnection we hope to take the opportunity to explore basic solar, solar wind, and magnetospheric physics as it relates to reconnection, taking examples from every discipline and thereby give the students a broad overview of these traditional topics that will be useful to them in the future.

Each year the summer school's governing board will determine a range of topics that spans the connected system from the Sun to Earth, through the solar system and heliosphere. Summer schools will incorporate material focused on physical processes and then relate these physical processes to the interconnected systems that couple the Sun, Earth, planets and the heliosphere. Therefore, space physical processes form an intellectual glue that connects the subdisciplines of space physics.

- *The curriculum will evolve as the subject of each summer's program changes. This is viewed as a learning program for all involved, including the faculty who volunteer to teach in the program. As the program grows, our vision of how best to accomplish the stated goals will grow as well.*

Every summer school will end with an afternoon of poster presentations by the students where they will be invited to share their research experience and show what work they are doing in their home institutions. This may include finished, published work or work only recently begun. The ability to explain a research idea is at least as important to scientific education as the ability to present finished results. The faculty of the summer school and the host institution will form the audience for these presentations.

Space Physics Summer School Operations

We need to establish 3 committees:

1. A governing board to assist in management and decision making.
2. A joint faculty that volunteers to teach the first year.
3. A list of faculty “affiliates” willing to teach in future years.

The first two committees are most critical to the initiation of the school. At present, this proposal and the ideas within it are the creation of too few individuals. We are willing to form the core that initiates the program, but to sustain the program will require the efforts of many researchers and educators from within the New England area and beyond.

Space Physics Summer School Assessment Assessment and Evaluation

Many educational programs have benefitted dramatically from educational assessment. External evaluator, Hilarie Davis, will work with the team to develop assessments for formative evaluation that provide feedback on the design and implementation of the summer school curriculum. Feedback will be gathered from students and teachers and open dialogues with organizers and lecturers will be held to, evaluate the relevance and suitability of the summer school material for undergraduates. Summative evaluation will focus on the effects of participation on the undergraduates understanding, interest and future plans initially through focus groups during the summer school and individual surveys at the end of the summer school, then in yearly follow up interviews and surveys with participating students. High school teachers will also be followed over time to understand the nature and extent of the effects of their participation in summer school on what and how they teach their courses.

Energy Transfer from the Solar Wind to the Solid Earth

Joshua Semeter, George Siscoe, Jeffrey Love, Vytenis Vasiliunas, Paul Song, Keith Siebert, Qian Wu, Alan Burns, Matthew Zettergren

Geospace as a stellar-planetary system supporting life

It is often said that we live in the presence of an average and unremarkable star. Following this logic, it must be concluded that the geospace system within which we have evolved is not singular in the universe. Indeed, the recent discovery of an Earth-like extra-solar planet suggests that hard observational evidence is on the horizon. How habitable environments arise in the universe must be considered among the most important and intellectually stimulating questions for mankind. As we begin to amass data on stellar-planetary systems in other parts of the universe, understanding our own solar-terrestrial system takes on renewed relevance and timeliness.

This general motivation can be used to frame a great many detailed science investigations relevant to this survey. This white paper emphasizes one area of investigation—solar wind-solid Earth coupling—and one particularly important approach—coupling of distributed measurements from the ground and from space through first-principles modeling.

Force transfer from the solar wind to the solid Earth

The interaction between the solar wind and the Earth's magnetosphere is analogous to a blunt object standing in a high Reynolds number flow. The net drag exerted by the solar wind is between 10 million and 100 million Newtons. This force must act on some mass, but it is not immediately obvious whether it is the mass that belongs to the magnetosphere or the mass that, by gravitational attachment, belongs to the Earth. A quick calculation makes apparent that is it not the magnetospheric plasma that stands off the solar wind for, if it did, it would be quickly blown away, contrary to experience. The only object within geospace massive enough to balance the drag exerted by the solar wind on the magnetopause is the Earth itself, and its gravitationally bound ionosphere/thermosphere.

The interaction of the solar wind with our magnetic planet produces a broad range of distributed responses. These are, in turn, measured by humans through an equally broad range of instruments and diagnostic strategies. Because of this observational accessibility, it has also become meaningful to develop detailed predictive models of the system. Despite all this, hard quantitative comparisons among theory, modeling, and observation has been sporadic, selective, and guided by the focused interests of individual communities (e.g., CEDAR, GEM, SHINE, USGS).

To break out of this balkanized approach, a paradigm shift is needed. We must view the solar wind, magnetosphere, ionosphere, thermosphere, and geomagnetic field as a coherently integrated system, tightly coupled from the bow shock to the Earths dipole. We must forge collaborations among theorists and experimentalists, the latter must include investigators focusing on both space-based and ground-based observations of the geospace system. Any new initiative of this type must be ambitiously quantitative, assimilating distributed measurements from ground and from space through first-principles local and global-scale modeling.

The thermospheric response: an enduring missing piece

Observations of the geospace system have understandably focused on effects that are easy to "see". These generally involve plasma related processes: electric and magnetic fields, and plasma particle populations. Of equal importance, but presenting a considerably greater observational challenge, is the heating and mechanical response of the Earth's thermosphere.

Observation have firmly established that the solar wind drives winds in the high-latitude thermosphere and, indirectly, at all latitudes during geomagnetic storms. Theory and modeling predicts that the force on the thermosphere is an order of magnitude bigger than the force that the solar wind exerts on the terrestrial system, the difference being made up by a force between the thermosphere and Earths dipole moment mediated by the region 1 current system [*Vasyliūnas*, 2007; *Siscoe*, 2009]. This force amplification has been termed the magnetospheric mechanical advantage. This rather surprising prediction can be tested by measuring, separately, the force exerted by the solar wind the force on the thermosphere, and the force on the geomagnetic dipole during a time when solar wind conditions are steady and the IMF is southward.

Evaluating this global force balance is within the grasp of current observational and modeling capabilities. Essentially, three global forces must be established:

- **Force exerted by the solar wind.** This is determined with global numerical MHD simulation using measured solar wind parameters as input and integrating the computed total stress tensor over a surface containing the terrestrial system.
- **Force on the thermosphere.** This requires measuring the acceleration of thermospheric winds over the area where the force is applied. For large disturbances, this means primarily the polar cap, where NSF has invested in new ionospheric and thermospheric diagnostic capabilities (RISR-N, RISR-C, PFISR, imaging Fabry-Perot interferometers.
- **Force on the Earth dipole.** This is measured by integrating the magnetic stress tensor over the Earth using globally distributed ground magnetometer data.

In the process of pursuing such an objective and the associated technical challenges, much serendipitous science, fundamental in its own right, will emerge. Issues such as thermospheric expansion, ion outflow, plasma convection, are expected to all be advanced by this project, in addition to diagnostic strategies, such as radar signal processing, statistical estimation, and multi-sensor fusion.

Societal implications

In addition to intellectual motivations, this initiative also has direct societal implications. Our understanding of the effects of space weather on geospace and its inhabitants is remarkably incomplete. Although the forces involved are negligible compared to forces associated with tropospheric weather and geological dynamics, the magnetic nature of these forces makes them highly consequential. Currents induced in transcontinental pipelines need to be accurately predicted for active mitigation of pipeline decay [*Gummow and Eng*, 2002]. Spacecraft communications may be interrupted as a result of ensuing ionospheric instabilities [*Lanzerotti*, 2009]. Astronauts and even airline crews can be harmed by extreme space weather events [*Getley*, 2004]. The effects of space weather are not all deleterious. Impulsive disturbances also provide a high-power, low frequency, signal for geological exploration via magnetotellurics [*Berdichevsky et al.*, 2010]. In a similar way, auroral displays produced by these disturbance provide a remote sensing diagnostic of distant magnetospheric dynamics [*Paschmann et al.*, 2003]. Each of these topics benefits significantly from a complete understanding of solar wind-terrestrial coupling. The proposed coalescence of theory, modeling, and observation defines a path towards a deeper understanding of this universal cosmic interaction and its immediate impacts on society and technology.

Is a dense network of ground-based sensors truly expensive?

The approach advocated in this proposal involves a close coupling of distributed observations from ground and from space. It is important to consider the differing cost paradigms associated with the two agencies that would typically fund instrumentation in these two domains of observation: NASA and NSF.

A NASA Explorer-class mission costs $200 Million. A single imaging Fabry-Perot Interferometer, capable of observing the line-of-sight neutral wind field, currently costs about $200,000, so 1000 times less. If a large network of such sensors are produced, the costs drops precipitously owing to volume purchasing of parts. If the budget of a typical monolithic satellite mission were used, instead, for ground-based instrumentation, a global scale network of geospace sensors could be produced that easily rivals the scientific efficacy of a NASA satellite mission.

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A cross-agency enabling effort focused on space weather observations and research-to-operation transition

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This short white is submitted to highlight a growing concern that there does not exist a robust coordinated national space weather program that (1) has an effective research-to-application pathway that produces operational tools, and (2) ensures sufficient space- and ground-based observations to provide adequate input to solar-terrestrial modeling.
In this white paper, we present an approach to addressing this concern by proposing a joint federal agency program involving NASA, NOAA and NSF.

Context:
National needs in the area of space weather informational and predictive tools are growing rapidly. As an example, recent studies, some of which were chartered by the highest government levels, have emphasized the need to understand the space weather threat to the North American power grid and to find ways to forecast Geomagnetically Induced Currents at critical grid nodes.

Many space weather studies have highlighted the need to collect substantial space weather information at observing sites ranging from interplanetary space to low-Earth orbit. In addition, the power of modern research and space weather model development can be better utilized to enable comprehensive, timely, and accurate operational space weather tools. At present, only a small fraction of the latest research and development results emanating from NASA, NOAA and NSF investments are being used to improve space weather forecasting and developing operational tools for the civilian sector. However, the mere production of space weather information is not sufficient to address the needs of those who are affected by space weather. A focused effort to transition knowledge to useful tools is required. There is no coordinated effort to adequately support research-to-applications transition efforts and to develop the tools required those who rely on this information. Moreover, no agency has both the resources and the mandate to provide the critical measurements needed to accurately specify the current state of the space environment, and to provide inputs and validation data for modern forecast models. To date, the majority of civilian space weather information and knowledge is obtained from NASA space-based missions and from NSF ground-based facilities and associated research, but there is not an effective framework to transition this knowledge and information to applications.

Proposal:
This whitepaper proposes a new approach to remedy this situation. Specifically, that NASA, NOAA and NSF work jointly under an umbrella program to enable space weather observations and provide space weather tools to the nation. The goal of this umbrella program is to provide space weather observations, to process space weather

measurements, to execute space weather models driven by space weather data sets, and to ultimately develop operational tools that are driven by the needs/requirements of and in collaboration with interested parties. A collaborative program between these three different agencies, rather than a program that independently augments one or more of these agencies, is needed because each of them bring unique and different capabilities, resources and mandates to the table. NASA brings diverse and robust flight opportunities and a broad infrastructure of fundamental scientific research and modeling for all aspects of Earth's space environment. NSF brings a mandate to fund the necessary ground measurement infrastructure and the associated scientific research and modeling infrastructure. NOAA brings selected flight opportunities and the mandate and infrastructure for implementing operation processes. All three of these capabilities and resources must be robustly coordinated for a successful program.

For this to become a reality, two necessary and critically important things must occur: (1) NASA, NOAA and NSF each must receive budget augmentation for the new program, and (2) a deliberate effort to clarify the roles and responsibilities of each federal agency that is consistent with their expertise and agency objectives must be undertaken.

We emphasize that this new activity must be implemented as a new program, which must not encroach on existing basic research activities, which also form the foundation of future developments in space weather specification and forecasting. In fact, to ensure that research is not adversely impacted, this new coordinating entity perhaps should not be implemented within the existing research organizations of the various agencies.

There are a number of substantial advantages should this space weather capability be implemented:

- The proactive and deliberate collaboration of research and operational development infuses the latest scientific insights immediately into space weather operations. Operational information in turn provides insights into the real-world, level of scientific understanding, and it points out additional direction for scientific research.

- The proactive and deliberate collaboration between research and operation provides ample opportunities for dual use development. Investment in space instrumentation development will infuse new capabilities into operational instrumentation, and operational observations will feed back information to the benefit of scientific studies. It is clear that the focus provided by the joining of science and operation within the same agencies provides substantial costs savings compared to cross-agency implementations.

- The proactive and deliberate collaboration of research and space weather operations provides a new synergy between space weather data and research data. Space weather data will directly support scientific research, e.g., a solar/heliospheric monitor at L5 will support fundamental solar and heliospheric research while providing a very valuable, space weather data source. This benefit extends to wherever space weather data are being collected, through the magnetosphere and down to measurements in the ionosphere-thermosphere-mesosphere domain. An example is the operational observations in the ionosphere and geosynchronous orbits where the vast majority of the impacts of space weather occur. This will greatly enhance the research in this area, and in turn close a existing gap in observations and system level modeling. Consequently, the research enabled by the availability of these additional data sources will provide a direct investment into future space weather capabilities.

- NASA, NOAA and NSF have experience flying and operating instrumentation on agency-owned or commercial spacecraft. A space weather mandate offers the opportunity to exploit these capabilities to the fullest. For example, space weather sensors could be flown on all future NASA and NOAA space missions, and partnerships could be actively pursued to fly space weather sensors on commercial spacecraft.

It must be noted however that effective transition of space weather information and knowledge to the user community for practical use has been found to be difficult and with limited success. Proven approaches, such as those within the applied Earth science and terrestrial weather community, can serve as a model to follow. This new program will learn from the most effective and successful research-to-operations transitioning efforts to ensure success of meeting the needs of the nation.

Summary:
In summary, NASA, NOAA and NSF have proven for many years to have the technical knowledge, skills, and dedication to develop the best space weather sensors and missions, and have marshaled a strong scientific community that uses these products to better understand space weather. These missions collect scientific data which can be used, often serendipitously, to develop and execute the world's best space weather models. It would be highly beneficial to bring this unique skill set to bear directly on the national needs for civilian space weather. A dedicated program for space weather research is needed to provide both the instrumentation and the expertise necessary to produce the next generation of space weather tools, including forecast models, and to help transition the latest space weather models and knowledge from research to operation. This final step is crucial in order to realize the societal benefits. This dedicated program must be a focused effort, funded separately from and without any adverse impact to research organizations. This whitepaper therefore proposes the establishment of a cross-agency entity with NASA, NOAA and NSF that (1) provides resources and leadership for an effective research-to-application effort that produces operational space weather tools, (2) that ensures sufficient space- and ground-based observations to provide adequate input to solar-terrestrial modeling, and (3) leverages the existing research modeling and instrumentation community through the NASA, NOAA and NSF organizations.

A NASA Applied Spaceflight Environments Office Concept

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1. Context.

The Nation's dependence on space assets is increasing in all aspects. Personal lifestyles are driven by connectivity of cell phones and home entertainment is dominated by satellite and cable feeds. Commercial dependence on connectivity in the banking, commerce, and retail business is increasing. As technologies using information from space based assets evolve, industries such as agricultural and energy are exploring new ways of becoming more efficient and precise. The medical applications for specific applications are beginning to rely on space communication. Military usage of the space assets for multiple reasons continues to be explored. Furthermore, as NASA prepares to send humans beyond low Earth orbit, understanding the environment to which they will be exposed is critical.

As a result, understanding the environment in which space assets operate has received considerable attention from federal agencies. The need to provide design, operational and predictive data and the need to develop tools to implement these in spaceflight systems is driving programs and strategies at various levels within federal agencies.

Evidence of the increased awareness of space weather is evidenced by the specific consideration of Congress in its budget deliberations and language. Many conferences, such as the recent SEASONS workshop (November 2010), are dedicated to various applied aspects of space environment and the impacts of space weather variability. During the 2010 Spacecraft Charging Technology Conference recognized, it was recognized that (1) spacecraft charging failures are likely to be more prevalent in the future due to the new higher voltage solar array systems, (2) spacecraft charging models are very dependent on degraded/exposed material property data, which often is not available, and (3) there is no centralized data collection for materials research and testing results.

2. Need for Coordination

Within the National Aeronautics and Space Administration (NASA), many organizations in many of its field centers have valuable expertise and have established efforts that attend to one aspect or another of designing systems to operate in the variable space environment. These efforts are varied and include (1) generating design data collected from materials and electronic parts space environments testing, (2) developing models that define the natural space environment used for systems design, and (3) providing tools used to improve operations of robotic and human activities.

In 2008-2009 the NASA Office of Chief Engineer sponsored a series of four reports generally titled "Space Weather Support to NASA Operations", that originally focused on the space radiation aspect of space weather, and subsequently broadened to a more robust and inclusive space weather perspective. These reports articulate NASA mission directorate space weather needs, describe the state of the art of space weather architecture, document the current trends and challenges in operational space weather, and portray a future operational space weather architecture for NASA.

Significant to this effort were the general findings, among which are:

- Improve intra- and inter-agency communication and cooperation in space weather activities
- Develop and implement standards and guidelines for space system radiation hardness and space environment risk mitigation
- Provide faster turn-around from research to operation with improved models

It should be noted that this activity has spawned a valuable working group within the agency called Space Weather Working Group (SWxWG), that maintains a consultant role and to help support Agency level decision-making in areas of space weather.

There is a recognized need to provide a method to coordinate the NASA space environment and space weather activities. There is an absence of a program that ensures the transition of space research products to users, and there is no NASA space environment/space weather point of contact for internal organizations or external agencies or customers. The NASA extended pool of expertise, broad range of activities, multiple testing and measurement facilities, diverse relevant engineering, spaceflight, and science data, valuable scientific models, and existing space environmental and effects engineering models should be coordinated in order for the agency to more effectively meet its own goals, and to play its role to support the nation in addressing the need to operate more effectively in the dynamic space environment.

3. Proposed NASA Applied Spaceflight Environments program

The NASA Applied Spaceflight Environment (ASE) office is designed to address the gap that exists between spaceflight environments knowledge and the application of this knowledge for multi-program, cross cutting NASA use and to transition of these products to external users. Presently, each NASA program/project must fund, establish, and develop their individual spaceflight environments products with the potential consequences of duplication of effort, over/under engineering, using inappropriate critical information, and acceptance of additional risk.

The ASE office will provide coordination across NASA, and funding for sustained multi-program support in three technical areas that have a demonstrated customer pull. These technical areas are:

- Natural Environments Characterization and Modeling

- Environmental Effects on Materials and Systems
- Operational Space Environments

In each of these areas, the ASE office would not conduct the efforts, but coordinate across NASA these efforts. It is envisioned as a NASA HQ office.

Note that "spaceflight environments" in this applied context is defined as all natural environments that influence the design, manufacture, development, and operation of spaceflight systems that function on extraterrestrial surfaces and in planetary atmospheres, geospace (including low Earth orbits) and interplanetary space.

The area of natural environments characterization and modeling will be focused on the design phase of programs. It will provide engineering design tools for space systems in the discipline areas of terrestrial and planetary atmospheres, ionizing radiation environments, plasma environments, extraterrestrial surfaces, interplanetary environments, and spacecraft charging. Existing but outdated, engineering design modeling products are available and are used extensively. Customer requests for products range between 200 and 400 per year. As an example, the ASE office would update coordinate the development of additional tools as needed.

Many NASA field centers have materials and parts testing and performance assessment through laboratory facilities and spaceflight experiments. Individual mission programs within NASA or external commercial aerospace and federal agency drive the current assessment efforts. However these activities are not coordinated. ASE would leverage all of these efforts to create one place where public information could be made available, and where those programs that needed this service could be guided to the appropriate facility within the agency.

The research to understand the dynamic nature of the space environment and what drives and modulates it is a vibrant science discipline called heliophysics. It is basically comprised of solar/space/plasma physicists, and aeronomers who study the mass and energy flow from with the Sun to the Earth, and throughout the Solar System. Valuable knowledge in the form of data, models, and theory is generated. However, there is very little effort, or funding incentive to transition this knowledge to operational and applied tools defined/required by users. ASE would coordinate the transition to operations with the many organizations within the Agency where it has invested in this science research. The ASE office would serve as the organization to fund and ensure this transition. It would be the point of contact within the agency to the other federal agencies, such as NOAA and DoD, and the commercial aerospace industry. ASE would use the valuable experience developed in other successful research-to-application programs, such as the Space Environments Effects project for engineering design tools, the Earth science projects SERVIR for disaster mitigation in developing nations, and SPoRT for mesoscale weather models to the NOAA National Weather Service.

To reemphasize a point made above, the ASE office is NOT proposed to conduct these activities, usurp existing efforts, or replace current collaborations. The ASE office will coordinate these efforts, leverage existing areas expertise and facilities across the field centers and provide resources to the appropriate organizations to develop non-existing design and research-to-application tools, and data products as needed. Responsibilities of the ASE office include:

- Fund the transition from research to application for new and existing models, and data sets
- Respond to internal and external to NASA user needs with product development and technical assistance
- Facilitate flight experiment opportunities
- Coordinate space weather observations for NASA operations
- Provide a coordinated effort to capture, archive, and distribute spaceflight environments and materials data
- Coordinate the development of spaceflight environment guidelines for design, development, manufacture, and operation
- Enable material advancement and space system improvements
- Provide a forum for Subject Matter Expert and user feedback/input
- Serve as the NASA entry/exit point for space environment products, to include
    - Test facilities, capabilities and expertise
    - Space weather products and data
    - Transition of research to applications

An incomplete list of the cooperative interface to the ASE office includes

- NASA Organization
    - Living With a Star (LWS)/SMD
    - Community Coordinated Modeling Center (CCMC)/GSFC
    - NASA EEE Parts and Packaging Program (NEPP)/GSFC
    - Meteoritic Environments Office (MEO)/MSFC
    - Orbital Debris Program Office (ODPO)/JSC
    - Space Radiation Analsis Group (SRAG)/JSC
    - Space Weather Working Group (SWxWG)/OCE
    - . . .
- Non-NASA Organizations
    - Space Weather Prediction Center (SWPC)/NOAA
    - DoD AFRL/NRL/Army
    - National Laboratories
    - Private Industry
    - International Partners
    - . . .

Space Weather Diamond (SWx◊)

A 10x improvement in real-time forecasting

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Introduction

This white paper promotes an applied heliophysics mission concept named "Space Weather Diamond" (SWx◊). Such a mission would facilitate the connection between science and societal needs (*e.g.*, improvements in space weather prediction) by providing an *order of magnitude* improvement over present-day L1 libration point monitors that measure the solar wind input to Earth's magnetosphere. Such concepts were explicitly called for in the Decadal Panel's Request for Information to the community. Additionally, the mission concept provides for significant science return, which is outlined in this paper.

Since the 1995 National Space Weather Plan was published, the heliophysics community has done an excellent job identifying and promoting the "applied" side of our science and the relevance to national (and international) infrastructure (*e.g.*, the recent NRC report: Severe Space Weather Events—Understanding Societal and Economic Impacts Workshop Report, 2008). The next logical step in acquiring measurements to improve space weather forecasting is a **sub-L1 platform**. The SWx◊ concept offers an opportunity to make that significant advancement without the use of solar sails or other exotic methods of in-space propulsion.

Mission Concept

Space Weather Diamond is based on a constellation of four platforms that are phased into eccentric heliocentric orbits but, from the perspective of a fixed Sun-Earth line, the spacecraft appear to orbit Earth. It was described in a St. Cyr *et al*. (2000) report, which was based on a study done internally at NASA-GSFC. The approach is based on a concept called "distant retrograde orbits" outlined by Ocampo (Ph.D., University of Colorado, 1996) describing a heliocentric orbit that remained in the vicinity of Earth. It is similar to a mission concept called "elliptical string of pearls" studied by NASA's Jet Propulsion Laboratory (Harris, JPL/Caltech D12611, 1995). The mission orbit is readily achievable using present day launch capabilities and lunar gravity assists.

The figure below shows the locations of four Space Weather Diamond spacecraft (A, B, C, D) at a given point in time. In this image, spacecraft "B" would provide the 10x early warning (compared to L1 platforms) of CMEs and interplanetary shocks. The eccentricity of this orbit is 0.10, which is about six times that of Earth. Lindsay *et al.* (1999) demonstrated the predictability of the Dst index using a variety of platforms inside Earth's orbit, and they concluded that a solar wind monitor located as distant as ~0:3 A.U. from Earth could provide reliable predictive capability. Based on recent STEREO results (*e.g.*, Simunac *et al.*, 2009), spacecraft "C" in this figure would provide early warning (~12 hours) of corotating solar wind features (CIRs) that can also be drivers of geomagnetic activity.

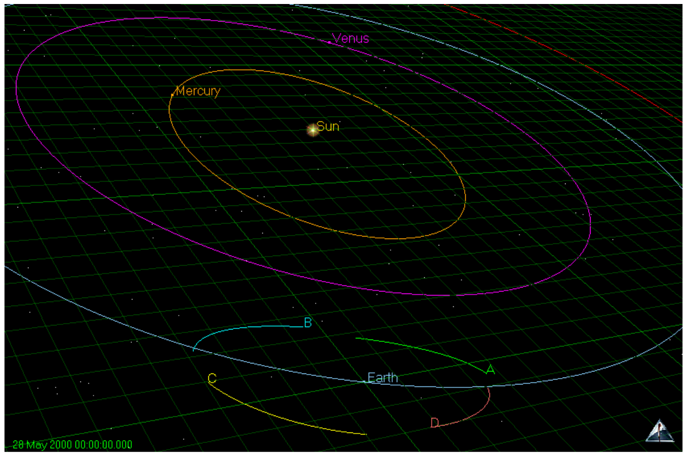

Figure 1: Four platforms of SWx◊ mission appear to circle Earth at ~0.1 A.U.

From the applied science perspective, SWx◊ would provide continuous transmission of solar wind conditions 0.1 A.U. upstream from Earth. This is important for forecasting the arrival of coronal mass ejections (CMEs), which are the primary cause of the most severe geomagnetic storms. CMEs, energetic particles, and other interplanetary disturbances can disrupt communications, navigation, and power infrastructure, as well as endanger human and robotic space explorers. The 2000 SWx◊ study assumed a 500 bit-per-second downlink (similar to the low rate telemetry provided by ACE (Zwickl *et al.*, 1998)), a 6W X-band transmitter, and a 0.5m dish antenna. Data acquisition at the maximum range is then possible with a 10m ground station antenna, which is available commonly through commercial vendors. The use of "beacons" on heliophysics spacecraft (*e.g.*, Zwickl *et al.*, 1998; St. Cyr & Davila, 2001) to telemeter relevant environmental parameters has led to a cottage-industry of space weather predictions.

The space weather monitoring platforms in our conceptual SWx◊ would be equipped with primarily *in situ* instrumentation to monitor solar wind plasma, and interplanetary magnetic field characteristics. Energetic particle instrumentation and a low-frequency radio instrument add the possibility of predicting the arrival time of interplanetary shocks inward of 0.1 A.U. The table below shows a straw payload and includes references for hardware and prediction heritage. An enhanced payload including remote sensing instruments would significantly increase the scientific return of the mission, and these potential science goals are considered in the next section.

Measurement	**Platform**	**Instrument Reference**	**Prediction Reference**
Magnetic field strength and direction	WIND, ACE, STEREO	Lepping et al. (1995), Smith *et al.* (1998); Acuna *et al.* (2008)	Recognized in 1960's (*e.g.*, see review by Baker *et al.*, 1984)
Solar wind proton	WIND, ACE,	Ogilvie *et al.* (1995);	Recognized in 1960's (*e.g.*, see

distribution function	STEREO	McComas *et al.* (1998); Galvin *et al.* (2008)	review by Burton *et al.*, 1975)
Low frequency radio emissions	WIND, STEREO	Bougeret *et al.* (1995); Bougeret *et al.* (2008)	Cremades *et al.* (2007)
Relativistic electrons	SOHO	Mueller-Mellin *et al.* (1995)	Posner (2007)
Energetic ions	ACE, STEREO	Stone *et al.* (1998); Mewaldt *et al.* (2008)	Cohen *et al.* (2001)

Potential Science with SWx◊

Beyond the obvious utility as a monitor of upstream solar wind conditions, there are numerous scientific possibilities for the SWx◊ concept. Here we describe several that we have considered, but a formal airing in the scientific community would certainly uncover additional ideas. The first science goal involves resolving the internal structure of interplanetary coronal mass ejections (ICMEs). We know that at 1 A.U. ICMEs have typically a 0.1-0.3 A.U. diameter, but details of their cross-sectional geometry are unknown at this time. Coronal white light observations would suggest near circular cross-sections (this is also the minimum energy configuration of the internal magnetic field); however, current state-of-the-art MHD heliospheric models predict significantly distorted cross-sections due to the interaction of the fast moving ICMEs and the ambient solar wind. Current 1 A.U. *in situ* observations can provide only a single track through the body of the ICME. These limited observations have been unable to distinguish between highly elliptical and circular cross sections. However, multiple measurements separated by ~0.1 A.U. would provide the necessary measurements to resolve this puzzle.

A second science goal would be to resolve the beam width of solar energetic particles (SEPs). The precise physical mechanism of solar energetic particle acceleration is still debated, and different proposed mechanisms have different predicted initial beam widths. Spacecraft separated by ~0.1 A.U. would provide the ideal platform to compare the SEP flux and energy profiles from the same event, thus providing valuable clues to the energization process.

A third science goal would employ triangulation studies with low frequency radio instruments. Single spacecraft observations heavily depend on the theoretical density profile of the solar wind in the inner heliosphere. A separation of ~0.1 A.U. is sufficient to allow precise tracking of shocks in the inner heliosphere, and multi-spacecraft triangulation relaxes this critical assumption.

If an enhanced payload included remote sensing instrumentation, then significant additional science would be possible. The first additional scientific aspect that SWx◊ would address is the critical need to perform 3D stereo imaging of the Sun--particularly active regions to obtain coronal magnetic structure using triangulation techniques. Magnetic field directions (but not magnitude) can be obtained for a large number of loops in the active region corona from stereo pairs of EUV images. These data can be compared with results from magnetic field extrapolation models. Initial comparisons using STEREO data and HINODE vector magnetic field measurements have shown that significant errors are found in the extrapolations of ALL models. The extrapolated field directions typically differ from the observed direction of the magnetic field by an average of 30 degrees. The STEREO spacecraft traversed these small elongations rapidly (in a few months) and very few active regions were available when these measurements were possible. Additional observations would provide unique checks on the validity of coronal magnetic field extrapolations which are used as the basis for most modeling and scientific research on the corona and heliosphere. Sandman *et al.* (Solar Physics, **259**, 2009) and others have concluded that there is a need for either more suitable (coronal rather than photospheric) magnetic field measurements or more realistic field extrapolation models. STEREO did not include magnetographs as part of the payload, so one approach to solving this problem would be to obtain vector magnetograph measurements from multiple vantage points such as would be offered by SWx◊.

A second scientific problem addressed by SWx◊ involves stereoscopic helioseismology, which has been widely discussed as a promising direction to extend that technique in the future. With stereoscopic helioseismology, new acoustic ray paths can be taken into account to probe deeper layers in the solar interior. The value of smaller separation angles for stereoscopic helioseismology is under study (Duvall, personal communication). Such measurements could help solve the puzzle of the solar cycle and advance our understanding of the operation of the solar dynamo.

What is Needed Next?

The objective of this white paper is to add a level of design maturity to the conceptual SWx◊. Heightened interest within NASA and other government agencies for sub-L1 solar wind measurements provides an applied science justification. SWx◊ would be "game-changing" for both heliophysics and for space weather prediction.

The instrumentation for SWx◊ is mature and at high technical readiness level, and the accommodation requirements for the space platforms have been accomplished numerous times successfully. The novel mission orbit can be achieved with existing launch capabilities. A rough cost estimate to station four platforms with this payload is that it should be similar to the THEMIS mission, a recent MIDEX (Angelopoulos, 2008), **making SWx◊ low cost with high benefit to operational customers**. Clearly the next step is to conduct a concurrent engineering exercise to validate the mission design, required power and communications, and to generate a cost estimate. This activity could be accomplished via NASA-GSFC Integrated Mission Design Center (IMDC) or JPL's Team X.

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Solar Orbiter: Exploring the Sun-Heliosphere Connection

Mission White Paper Submitted to the Decadal Survey Panel on Solar and Heliospheric Physics
[From the Solar Orbiter Assessment Study Report, ESA/SRE(2009)5]

2010-11-08

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We live in the extended atmosphere of the Sun, a region of space known as the heliosphere. Understanding the connections and the coupling between the Sun and the heliosphere is of fundamental importance to addressing the major scientific questions outlined in the 2010 NASA Science Plan for the Science Mission Directorate Heliophysics Division: What causes the Sun to vary? How do the Earth and the heliosphere respond? What are the impacts on humanity? The heliosphere also represents a uniquely accessible domain of space, where fundamental physical processes common to solar, astrophysical and laboratory plasmas can be studied under conditions impossible to reproduce on Earth, or to study from astronomical distances.

The results from missions such as Helios, Ulysses, Yohkoh, SOHO, TRACE and RHESSI, as well as the recently launched Hinode, STEREO, and SDO missions, have formed the foundation of our understanding of the solar corona, the solar wind, and the three-dimensional heliosphere. Each of these missions had a specific focus, being part of an overall strategy of coordinated solar and heliospheric research. However, an important element of this strategy has yet to be implemented. None of these missions have been able to fully explore the interface region where the solar wind is born and heliospheric structures are formed with sufficient instrumentation to link solar wind structures back to their source regions at the Sun. For example, Helios 1 and 2 carried no imaging instruments. With previously unavailable observational capabilities provided by the powerful combination of in-situ and remote-sensing instruments and the unique inner-heliospheric mission design specifically tailored for the task, Solar Orbiter will address the central question of heliophysics: ***How does the Sun create and control the heliosphere?*** This primary, overarching scientific objective can be broken down into four interrelated scientific questions, all of which have strong, direct relevance to the ESA Cosmic Vision theme "How does the Solar System work?" The four top-level scientific questions being addressed by Solar Orbiter are:

- How and where do the solar wind plasma and magnetic field originate in the corona?
- How do solar transients drive heliospheric variability?
- How do solar eruptions produce energetic particle radiation that fills the heliosphere?
- How does the solar dynamo work and drive connections between the Sun and the heliosphere?

These are outstanding fundamental questions in solar and heliophysics today. By addressing them, we will make major breakthroughs in our understanding of how the inner solar system works and is driven by solar activity. To answer these questions, it is essential to make *in situ* measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that they are still relatively pristine and have not had their properties modified by subsequent transport and propagation processes. This is one of the fundamental drivers for the Solar Orbiter mission, which will approach the Sun to within 0.28 AU. Relating these *in situ* measurements back to their source regions and structures on the Sun requires simultaneous, high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane. The resulting combination of in-situ and remote sensing instruments on the same spacecraft, together with the new, inner-heliospheric perspective, distinguishes Solar Orbiter from all previous and current missions, enabling breakthrough science which can be achieved in no other way. The high priority of the science objectives of Solar Orbiter have been consistently reflected in community science planning activities, *e.g.*, by including this mission and its scientific goals in such recent reports as the 2003 Decadal Survey (Lanzerotti committee) and the 2009 Heliophysics Roadmap. Solar Orbiter is an ESA-led mission with significant contributions from NASA.

Mission Design. A mission profile for Solar Orbiter has been developed that will, for the first time, make it possible to study the Sun with a full suite of in-situ and remote-sensing instruments from inside 0.28 AU and provide imaging and spectral observations of the Sun's polar regions from out of the ecliptic. This proximity to the Sun will also have the significant advantage that the spacecraft will fly in near synchronization with the Sun's rotation, allowing observations of the solar surface and heliosphere to be studied from a near co-rotating vantage point for almost a complete solar rotation. The baseline mission is planned to start on 4 January 2017 with a launch on a NASA-provided launch vehicle from Cape Canaveral, placing the spacecraft on a ballistic trajectory that will be combined with planetary gravity assist maneuvers (GAM) at Earth and Venus. The initial resonance with Venus is 4:3, switching to 3:2 after the third Venus GAM. The resultant operational orbit has an orbital period of 168 days, a perihelion radius of 0.28 AU and an initial solar inclination of 7.7°. A series of Venus gravity assists (every 450 days) will then increase the solar inclination. The end of the nominal mission occurs 7.5 years after launch, when the orbit inclination relative to the solar equator exceeds 25°. The inclination may be further increased during an extended mission phase using additional Venus GAMs, to reach a maximum of 34°.

Scientific Payload. The scientific payload of Solar Orbiter will be provided by ESA member states and NASA, and has already been selected and funded for the definition phase through a competitive AO selection process. The 10 principal investigator-led hardware investigations are:

The in situ instruments:

● The Solar Wind Analyser (SWA) instrument suite (C. J. Owen, PI, UK) will fully characterize the major constituents of the solar wind plasma (protons, alpha particles, electrons, heavy ions) between 0.28 and 1.4 AU.

● The Energetic Particle Detector (EPD) experiment (J. R. Pacheco, PI, Spain) will measure the properties of suprathermal ions and energetic particles in the energy range of a few keV/n to relativistic electrons and high-energy ions (100 MeV/n protons, 200 MeV/n heavy ions).

● The Magnetometer (MAG) experiment (T. S. Horbury, PI, UK) will provide detailed in-situ measurements of the heliospheric magnetic field.

● The Radio and Plasma Waves (RPW) experiment (M. Maksimovic, PI, France) will measure magnetic and electric fields at high time resolution and determine the characteristics of electromagnetic and electrostatic waves in the solar wind from almost DC to 20 MHz.

The remote sensing instruments:

● The Polarimetric and Helioseismic Imager (PHI) (S. K. Solanki, PI, Germany) will provide high-resolution and full-disk measurements of the photospheric vector magnetic field and line-of-sight velocity as well as the continuum intensity in the visible wavelength range.

● The Extreme Ultraviolet Imager (EUI) (P. Rochus, PI, Belgium) will provide image sequences of the solar atmospheric layers from the photosphere into the corona.

● The Spectral Imaging of the Coronal Environment (SPICE) EUV Spectrograph (D. M. Hassler, PI, U.S.) will provide spectral imaging of both the solar disk and in the corona to remotely characterize plasma properties of regions at and near the Sun.

● The Spectrometer/Telescope for Imaging x-rays (STIX) (A. O. Benz, PI, Switzerland) provides imaging spectroscopy of solar thermal and non-thermal x-ray emission from ~4 to 150 keV.

● The Multi Element Telescope for Imaging and Spectroscopy (METIS/COR) Coronagraph (E. Antonucci, PI, Italy) will perform broad-band and polarized imaging of the visible K-corona and narrow-band imaging of the UV and EUV corona.

● The Solar Orbiter Heliospheric Imager (SoloHI) (R. A. Howard, PI, U.S.) will image both the quasi-steady flow and transient disturbances in the solar wind over a wide field of view by observing visible sunlight scattered by solar wind electrons.

Spacecraft. The Solar Orbiter spacecraft is a Sun-pointed, 3-axis stabilized platform, with a dedicated heat shield to provide protection from the high levels of solar flux near perihelion. Feed-throughs in the heat shield (with individual doors) provide the remote-sensing instruments with their required fields-of-view to the Sun. Two-sided solar arrays provide the capability to produce the required power throughout the mission over the wide range of distances from the Sun using rotation about their longitudinal axis to allow switching between faces, as well as control of the solar aspect angle to allow management of the array temperature throughout the mission, particularly during closest approach to the Sun. An articulated high temperature high gain antenna provides nominal communication with the ground station, and a medium gain antenna and two low gain antennas are included for use as backup. The design drivers for the Solar Orbiter spacecraft come not only from the need to satisfy the mission's technical and performance requirements, but also from the need to minimize the total cost of the mission. The adopted philosophy is therefore to avoid technology development as far as possible, in order to maintain the cost-cap of the mission. The design of Solar Orbiter has therefore incorporated BepiColombo technology items where appropriate. Furthermore, design heritage from the Express series of missions, with their goal of rapid and streamlined development, has also featured heavily in the Solar Orbiter spacecraft design.

Mission Operations. One of the strengths of the Solar Orbiter mission is the synergy between *in situ* and remote-sensing observations, and each science objective requires coordinated observations between several *in situ* and remote-sensing instruments. Another unique aspect of Solar Orbiter, in contrast to near-Earth observatory missions like SOHO, is that Solar Orbiter will operate much like a planetary encounter mission, with the main scientific activity and planning taking place during the near-Sun encounter part of each orbit. Specifically, observations with the remote-sensing instruments will be organized into three 10-day intervals centered around perihelion and either maximum latitude or maximum co-rotation passages. As a baseline, the *in situ* instruments will operate continuously during normal operations. Another important aspect of this mission, from a science operations standpoint, is that every science orbit is different, with different orbital characteristics (Sun-spacecraft distance, Earth-spacecraft distance, etc.). Science and operations planning for each orbit is therefore critical, with specific orbits expected to be dedicated to specific science problems. This will be similar to what has been used successfully in ESA's SOHO mission's Joint Observation Programs (JOPs).

Science Management and Data Archiving. Planning for Solar Orbiter is already quite mature, with science planning in particular already under way. Science teams have been formed for each science problem, which includes representatives from each instrument team, as well as theorists and modelers from the broader international scientific community. Data archiving will follow the same model as previous ESA PI-led solar and heliospheric missions, such as SOHO, with data made available to the scientific community through the ESA science data archive, which will be mirrored in the U.S.

International Cooperation. Solar Orbiter is an ESA-led mission, but has strong NASA participation and substantial funded commitment. Specifically, NASA plans to provide the launch on an evolved expendable launch vehicle (EELV), and significant parts of the scientific payload. NASA selected the stand-alone instruments SPICE and SoloHI, as well as providing sensors SWA-HIS (Heavy Ion Sensor, S. Livi, NASA PI, SwRI) and EPD-SIS (Suprathermal Ion Spectrograph, G. Mason, NASA PI, JHU/APL).

The mission also has important synergies with NASA's Solar Probe Plus mission, and coordinated observations are expected to enhance greatly the scientific return of both missions. Solar Orbiter was also studied in the context of NASA's Solar Sentinels mission as part of HELEX. In the overall international context, Solar Orbiter is ESA's primary contribution to the International Living With a Star (ILWS) initiative, and joint studies incorporating data from all missions operating in the inner heliosphere (or providing remote sensing observations of the near-Sun environment) will contribute greatly to our understanding of the Sun and its environment.

Conclusion. Solar Orbiter is a mature mission with focused and timely scientific objectives directly relevant and important to the NASA and ESA science programs. Its powerful combination of *in situ* and remote sensing instruments and unique mission design make Solar Orbiter ideally suited to answer several of the outstanding, fundamental questions in solar and heliophysics today. By addressing them, Solar Orbiter will achieve major breakthroughs in our understanding of how the inner solar system works and how it is driven by solar activity, as well as improve our understanding of fundamental physical processes common to all solar, astrophysical, and laboratory plasmas.

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Multi-scale Electrodynamics of Magnetosphere-Ionosphere Interactions

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Electrodynamics of magnetosphere-ionosphere interactions at high altitude involving ultra-low-frequency Alfven waves have been studied extensively for almost 50 years [e.g., *Radoski*, 1967; *Cummings et al*., 1969]. The initial goal of these studies was to explain geomagnetic pulsations in Pc5-Pc6 frequency range in the auroral zone as measured by ground-based magnetometers. Later, interest in Alfvén waves steadily increased when observations showed that discrete fluxes of keV electrons causing discrete aurora were often correlated with intense, localized electromagnetic disturbances, which were sometimes interpreted as dispersive Alfvén waves [*Xu et al.*, 1993; *Marklund et al*., 1994; *Samson et al.*, 1991, 1996; *Lotko et al.*, 1998; *Chaston et al.*, 2002, 2003; *Figueiredo et al*., 2005]. Observations also showed that these waves frequently correlated with ion outflows, density cavities, and heating and redistribution of plasma between the ionosphere and the magnetosphere [e.g., *Lundin et al*., 1994; *Stasiewicz et al*., 1998; *McFadden et al*., 1999; *Lynch et al*., 1999; *Chaston et al*., 2000, 2006], which meant that they play an extremely important role in magnetosphere-ionosphere (MI) interactions.

In classical studies of MI coupling, two parts of the system were considered separately, and the eigensolutions of one part have been used as a known parameter to find the solution of another part. The failure of this approach can be illustrated by the fact that despite numerous theoretical and experimental studies, one of the most fundamental questions of auroral studies, namely, what causes the formation of narrow, discrete auroral arcs, has not been answered yet [e.g., *Borovsky*, 1993]. Comprehensive reviews of these studies [e.g., *Stasiewicz et al*., 2000; *Pashmann et al*., 2002; *Keiling*, 2009] reveal that they can be split into two groups depending on which part of the MI system is considered to be the "main maker" of the discrete aurora. The first group explains them with pure magnetospheric effects. Two of the most popular mechanisms from this group are 1) phase mixing of Alfvén waves propagating toward the ionosphere across strong transverse gradients in the Alfvén velocity [e.g., *Genot et al*., 1999] and 2) magnetospheric field line resonances (FLRs) [*Southwood*, 1974, *Chen and Hasegawa*, 1974, *Samson et al*., 1992].

Another group of studies explains the formation of discrete arcs by the active ionospheric response (feedback) on dynamics of large-scale magnetic field-aligned currents (FACs) interacting with the ionosphere. Probably the most well-known example from this group is ionospheric feedback instability [*Atkinson*, 1970] inside the so-called ionospheric Alfvén resonator (IAR) [*Polyakov and Rapoport*, 1981] formed by the ionosphere and the maximum in the Alfvén speed at the altitude ~1 R_E. The ionospheric feedback instability has also been used to explain small-scale, intense, electromagnetic structures and discrete auroral arcs in the global magnetospheric resonator [*Sato*, 1978; *Watanabyet al.*, 1993; *Pokhotelov et al.*, 2002].

Studies from these two groups depend on the existence of some resonance cavities in the magnetosphere or a strong transverse inhomogeneity in the background plasma, or both. Sometimes these requirements are satisfied and sometimes not. For example, recent observations from the FAST, Polar, and Cluster satellites [e.g., *Wygant et al*., 2000; *Keiling et al*., 2001, *Figueiredo et al*., 2005] show that a significant fraction of the aurora is powered by intense Alfvén waves propagating along the magnetic field lines passing through the plasma sheet boundary layer. These magnetic field lines are considerably stretched in the tailward direction and not always well defined. This fact makes it hard to explain these waves with classical FLR theory, which required closed magnetic field line geometry, although some attempts have been made [e.g., *Rankin et al*., 2000]. At the same time, these structures have frequencies much lower than the frequency predicted by the IAR theory, and they are detected in the magnetosphere considerably above the altitude where the upper boundary of the IAR makes it hard to use IAR theory to explain them.

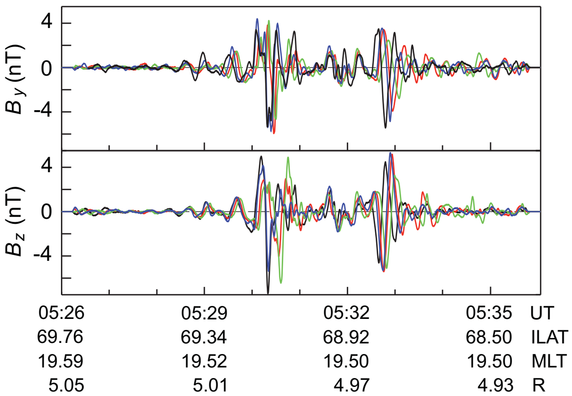

Figure 1. Small-scale ULF waves detected by the Cluster satellites in the magnetosphere [*Karlsson et al*., 2004].

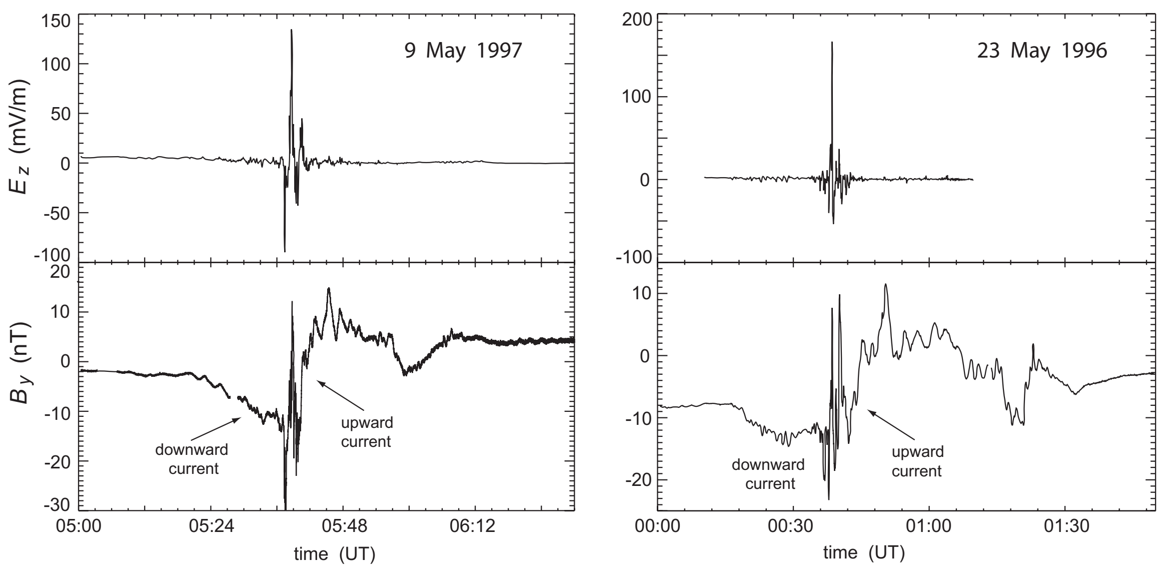

Figure 2. North-South electric field and East-West magnetic field measured by the Polar satellite on May 9, 1997 (Left) and on May 23, 1996 (Right) [*Keiling et al*., 2005].

For example, Figure 1 (adopted from *Karlsson et al*. [2004]) shows small-scale electromagnetic structures measured by Cluster satellites on 19 May 2002 at an altitude of 4 R_E. **“**The periods of these waves are 20-40 s, which is not consistent with periods associated with either the Alfvenic ionospheric resonator typical field line resonances or substorm onset related Pi2 oscillations**”** [*Karlsson et al*., 2004]. A number of similar observations have been published by the Cluster group from the University of Stockholm [e.g., *Johansson et al.*, 2004; 2005; 2006]. These observations are in qualitative agreement with data from the Polar satellite (see Figure 2), which demonstrate intense, small-scale electromagnetic structures in the plasma sheet boundary layer at the geocentric distance between 5 and 6 R_E [*Keiling et al*., 2005]. (Polar, as well as any other single spacecraft, cannot resolve spatial and temporal features of the observed structures as the Cluster did.) Thus, data reveals that the generation and spatiotemporal properties of small-scale, intense electromagnetic waves observed in the magnetosphere are not explained yet.

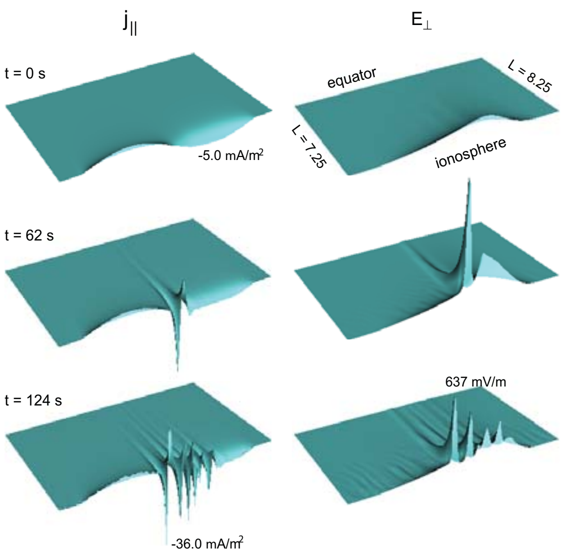

Figure 3. Interactions between two upward and downward large-scale FACs and the ionosphere. [*Streltsov and Lotko*, 2004].

The major progress in understanding spatial characteristics (forms and sizes) and temporal dynamics (frequencies and growth rates) of electromagnetic and density structures at low altitudes has been achieved in simulations where the active ionsospheric response (or, basically, dynamics of the ionsospheric plasma) has been self-consistently included in the models describing propagation of ULF waves in the magnetosphere [e.g., *Streltsov and Lotko*, 2004; 2005]. Figure 3, which is adopted from these studies, illustrates the generation of small-scale, intense electric fields and currents by such interactions. It shows that in excellent agreement with the observations illustrated in Figure 2, the small-scale waves are generated in the ionosphere on the boundary between the upward and downward current channels. This happens because a strong gradient in the ionospheric conductivity is formed in this location, and the perpendicular electric field in the ionosphere associated with the pair of FACs maximizes here.

Therefore, a self-consistent, multi-scale, multi-fluid electromagnetic coupling between the ionosphere and the magnetosphere is the key factor explaining various electromagnetic, luminous, and plasma structures in the ionosphere and the low-latitude magnetosphere. In this coupling, the ionosphere and the magnetosphere should be considered as a single,

unified, complex system, and it should be studied as such with corresponding numerical models.

We propose to include in the nearest NASA plans the development and simulation of coupled, numerical models describing in quantitative detail the dynamics of multicomponent ionospheric plasma (like the SAMI3 model, developed at NRL [*Huba et al*., 2000]) and the propagation of multi-scale ULF waves/magnetic field-aligned currents in the magnetosphere (like the multifluid, dispersive MHD model developed at Dartmouth College [*Streltsov et al*, 2008]). These models will be verified by comparing the numerical results and experimental data measured by satellites, sounding rockets, ground radar, magnetometers, and optical cameras in the auroral and sub-auroral zone. These observations include data from past/current NASA missions like FAST, Polar, Cluster, and THEMIS, as well as data from sounding rockets (CASCADE-2 and the future experiment, MICA), and THEMIS ground optical imagers.

The ultimate goal of these comprehensive, multi-fluid, wave-particle numerical models with predictive capabilities will be not just to EXPLAIN *post factum* relevant observations, but also to PREDICT with quantitative detail multi-scale dynamics of the electric fields, currents, and plasma in the low-altitude magnetosphere and the ionosphere for different geomagnetic conditions. These quantitative, detailed predictions will be verified with results from active experiments in the near-Earth space environment. One example of such active experiments is the generation of large-amplitude ULF/ELF electromagnetic waves in the magnetosphere by heating the ionosphere with powerful RF transmitters (like High Frequency Active Auroral Research Program (HAARP) facility in Alaska). Preliminary results from these experiments already demonstrate the potential capability of such transmitters to generate large-amplitude waves detectable on the ground [e.g., *Blagovechenskay et al.*, 2000; *Streltsov et al*., 2010] and on satellites [e.g., *Robinson et al*., 2000]. The major disappointment with these experiments is that their results are not repeatable; they significantly vary from one experiment to another. There are two reasons for these variations. The first reason is that current geophysical probes measuring parameters of the ambient media and results from experiments are not sensitive enough. This problem can and will be resolved in the near feature by the next steps in the development of the corresponding hardware. For example, it is highly desirable to have an Incoherent Scatter Radar (ISR) at the HAARP facility. This powerful instrument will fill a large gap in current diagnostic capabilities and will allow scientific results to be generated at a much faster rate. This is particularly important for next generations of active experiments where the parameters of the heater should change dynamically in response to the variation of parameters of the ambient media.

The second reason is that currently there is not a single numerical/physical model describing MI coupling with the necessary level of detail to predict the outcome from the experiment for different geomagnetic conditions. W**e evaluate the development of such self-consistent, multi-**

scale, multi-fluid wave-plasma numerical models describing coupling between the ionosphere and the magnetosphere as one of the highest priorities for NASA. These models will be developed, tuned, and tested with a great number of experimental results already collected on the ground, in the high latitude ionosphere and magnetosphere, but the scope of applications of these models will be much broader. It is anticipated that with some minor modifications, primarily related to the background parameters, they will be used to explain results from past and current observations and to plan future satellite and sounding rocket missions at high latitudes (auroral and sub-auroral zones), middle latitudes (outer radiation belt), and low latitudes (low-latitude ionospheric Alfven resonator, inner radiation belt, equatorial spread-F). There is no doubt that these models will significantly contribute to an understanding of important scientific questions facing solar and space physics today.

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Heliophysics System Science and Funding for Extended Missions
Allan J. Tylka

I have served on the last three Heliophysics Senior Review (HSR) Panels, in 2005, 2008, and 2010. Based on those experiences, I am writing to offer some comments and recommendations for your consideration. Please note that I am writing you as an individual, and nothing that I say here should be imputed to my employer, which is another government agency. For the record, I note that I am not nor ever have been a member of a mission or instrument team. (Undoubtedly, this is why I keep getting tapped for the HSR.) However, throughout my career, a large part of my research has involved making use of data from heliophysics missions and has been funded by the Heliophysics GI, SR&T and LWS/TR&T programs.

This document is broken into two parts. As background, in Section 1, I briefly review findings and comments from the 2010 HSR. In Section 2, I offer four suggestions and recommendations on MO&DA funding for Heliophysics extended missions.

Section 1: Background: The 2010 Heliophysics Senior Review

The 2010 Heliophysics Senior Review differed from the last two senior reviews in important ways. In the previous HSRs, the mission teams were asked to submit both 'optimal' and 'in-guide' budgets. The former were designed to maximize the scientific impact of the mission while still recognizing the very tight fiscal constraints that NASA faces. Although the MO&DA budgets have never been sufficient to support all missions at the optimal level, it was the happy task of the HSR Panel to identify the missions that made the most compelling scientific cases for a higher budget.

In the 2010 HSR, circumstances were very different. First, mission teams were instructed to present only "minimal science" budgets. Second, the Senior Review Panel was informed of the need to cut the prospective MO&DA "minimal science" budget from $59.5M to $54.7M in FY11 and from $57.9M to $51.8M in FY12. (These numbers do not include the Heliophysics GI program, which also falls under the "MO&DA" line.) Moreover, due to the projections of reduced funding levels in future years and the impact of new missions moving from their prime mission phase to the extended mission budget, the latter will be under-funded, by the order of $5M per year in the out-years.

In assessing the value and costs of extended missions, the Panel noted several facts:

(a) Overall, the Panel found that the mission teams have been responsive to the call for "minimal science funding". In fact, in nearly all cases, the mission teams have been aggressive in reducing operating costs.

(b) The Panel found that NASA, in consultation with the science community, has done a good job in terminating satellites and/or instruments made obsolete by newer missions.

(c) The Panel found that the remaining missions in the Heliospheric System Observatory (HSO) are complementary, not duplicative. Each mission occupies a unique vantage point, in terms of either its instruments and/or orbits.

(d) The Panel rejected the notion that mature missions, well into their extended phase, are easy targets for cuts since these missions already have a large database in hand. This notion overlooks the growing power of the HSO, due to the addition of new missions, such as Hinode, IBEX, and SDO, and how the context provided by these new missions increases the potential value of new data from older instruments. The long baseline of existing instruments also has intrinsic value, in the light they shed upon phenomena with long timescales, which we are only beginning to understand. It is also short-sighted to assume that a mission can only make discoveries during its "prime" phase.

(e) In the opinion of the Panel, the Heliophysics MO&DA is already operating at inadequate levels of funding. These funding levels jeopardize HSD's ability to meet its objectives for Heliospheric System Science. These concerns are further aggravated by the instability in support for Helio GI, SRT, and LWS/TRT programs, which utilize the HSO datasets.

Section 2: Suggestions and Recommendations

1. The Priority of Heliophysics System Science

Heliophysics is an exciting part of NASA's science portfolio. Like our colleagues in NASA's other science divisions, we explore fundamental processes that challenge our ability to understand Nature. However, we also address challenges (like space weather and space climate) with direct implications for our Nation's economy and security. These two aspects of our research meet in the Heliophysics Division's commitment to Heliospheric System Science. System Science is larger than any single mission, and understanding the heliospheric system necessarily requires sampling this vast region of space at multiple locations and with an array of sensitive, robust instruments measuring a broad spectrum of physical quantities.

The Heliophysics System Observatory (HSO), the product of many years of effort and billions of dollars in investment, is our prime tool for advancing heliospheric system science. Given NASA's overall budget constraints, we must identify the most cost-effective way of doing system science. In particular, the marginal costs of operating of an existing mission are very small compared to costs of developing and launching a new mission. It may therefore be argued that the best way of leveraging previous investments and of addressing system-science objectives is to collect data from existing spacecraft and instruments until they fail or are rendered obsolete by a new mission.

Unfortunately, once a mission has completed its first 3-5 years of operation, NASA necessarily starts to perceive that mission as a liability, rather than an asset. This attitude is driven simply by pressure on the mission-operations budget. This attitude must be changed. Eventually every satellite will fail or be superseded by a new mission with better technology. But until that happens, our obligation to taxpayers should be to squeeze as much science out of every mission as we can. NASA should explicitly recognize that our satellites have the ability to deliver unique and useful data for many years – 10, 15, maybe even 22 years! – and budget accordingly.

So here's the big question: given the Heliophysics Division budget of ~$600M, how is it decided that continued operation of existing missions is worth no more than $55M? Does this amount come from an effort to maximize the science return from the HSO?   Or does the does the budget line for extended-mission operations come at the bottom of the HSD queue, garnering the remainders of whatever may be left after paying for new missions and other mandates? Given what I have seen in the Senior Reviews, I believe that the situation is the latter: the budget for the HSO and for extended missions is literally "what is left?"

Since Heliophysics has proven to be an observationally-driven science, the essential need for and inherent value of new missions is beyond question. Appropriately, new missions will always get the lion's share of the Heliophysics budget. Nevertheless, the Decadal Survey provides an opportunity to examine the larger question of the budgetary balance between extended-phase and new missions. In particular, when it comes to system science, should we 'put our money where our mouth is' and assert that funding adequate to exploit fully the HSO should be at the top of the Heliophysics priority queue?

Changing the order of priorities, and the balance between ongoing and new missions, are high-level questions. HQ officials rightfully argue that, at some level, their hands are tied by congressional mandates. It therefore requires congressional action to recognize the prime importance of adequate funding for extended-mission operations. The Decadal Survey is our best opportunity for conveying this message to Congress.

2. The Senior Review Process

Many people will undoubtedly blanche when they read about funding going on for 10-20 years. It is important to emphasize that we are not creating sinecures. Ongoing funding for extended missions must be limited and strictly controlled; it cannot in itself be allowed to become the primary source of income for individuals or institutions.

For these reasons, the Senior Review process, or something like it, must still play a critical role, in assessing the ongoing health of instruments and spacecraft, identifying redundancies with newer mission, and evaluating the extent to which the mission's data are still valuable to heliophysics research, as evidenced by peer-reviewed publications.
But once the Senior Review has given a positive judgment on these issues, NASA should be charged to find adequate resources to support the ongoing missions. This scenario is the exact opposite of what has happened in recent Senior Reviews, where the panel's primary duty has been to "find out what we can turn off with doing the least damage."

3. External Funding for Extended Missions

Here's an idea that might initially be rejected as outlandish or distasteful. But think about it:

NASA should explore sources of out-of-house funding for extended missions. In the 2010 Senior Review, 10 of the 13 reviewed missions had FY11 budget requests in the range of $1M-$5M per year. The aggregate cost is large. But just imagine: “The Google Voyager Interstellar Mission” or “The Microsoft Advance Composition Explorer”.

Universities have sold “naming rights” for decades, and to many corporate entities, the amounts of money we are talking about are not large. For them, spending a few million dollars per year to be identified with these missions might be very appealing. After all, our science inspires the next generation of scientists and engineers who will develop and use their technology. Clearly the corporate support could not be used to fund work by civil servants. But universities and private corporations, where a lot of the MO&DA work gets done, could accept funding from private sources. Congressional action might be required to allow these arrangements. If that is so, an endorsement from the Decadal Survey would be the first step.

4. Relationship to Research and Analysis (R&A) Funding

Support for the operation of extended missions should not be allowed to become competition for research and analysis (R&A) funding. That has happened twice in recent years, in which the Heliophysics GI competition has been cancelled because of the squeezed MO&DA budget. It should be recognized that the extended-mission operations and research and analysis funding are inherently dependent on each other and complementary. We cannot do system science without the data from extended missions, and it certainly makes no sense to collect and archive data if no one is funded to do science with them.

Global Airglow Interferometer Limb-scanner (GAIL) A New Thermospheric Wind Instrument

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Summary of the Science Concept

In this white paper we describe a new concept of high altitude limb-scan instrument: Global Airglow Interferometer Limb scanner (GAIL), which will measure the thermospheric winds (200 to 300 km) by recording wind induced Doppler shift in the O 630 nm airglow emission day and night. Because GAIL will be mounted on a circular high orbiting satellite (6500km), it will be able observe a very large area at any given time and will, for the first time, provide a nearly synoptic global view of the thermospheric wind field. GAIL can measure thermospheric winds on 8 measurement tracks along its orbit and cover 86 percent of the globe in one orbit (~ 4 hours). The thermospheric wind error will be about 5 m/s for 2 second exposure time. GAIL may also be able to measure day time ion drift by looking at the O+ 732 nm emission. GAIL can cover both polar caps and equatorial region with one satellite. It will provide 24-hour local time coverage at the equator in one orbit. In mid-latitudes the local time coverage will be at least 16 hours. That kind of local time coverage will be sufficient for characterizing various tidal components without large aliasing as in the case of asynoptic data from current and past satellites. The instrument can be extremely useful for ionosphere model assimilation and will have a great impact on space weather forecast capability given the strong effect thermospheric wind has on the ionosphere.

1. Description of Science Concept

1.2 Rational for Global Thermospheric Wind Coverage

Ion neutral interaction is one of the research focus areas for the “Open the Frontier to Space Environment Prediction” identified by the NASA Heliophysics 2009/2010 roadmap (F3, p6). Several priority investigation questions are as follows: What governs the coupling of neutral and ionized species? How do coupled middle and upper atmospheres respond to external drivers and to each other? What is responsible for the dramatic variability in many of the state variables describing the ionosphere-thermosphere mesosphere (ITM) region? How do the magnetosphere and the ionosphere/thermosphere systems interact with each other? In order to address these questions, a global view of thermospheric wind pattern is a must. Lack of the thermospheric wind data has hampered further progress on these important questions. Thermosphere/ionosphere interaction is a key to understand the ionosphere and has a great implication for space weather. Such interaction is important from the polar cap to the equatorial region. In each of the regions the issues are different yet equally challenging and all require thermospheric wind information.

At high latitudes, the thermosphere absorbs the energy from solar wind/magnetosphere via the ionosphere. It receives the energy from electron precipitation and joule heating. The joule heating is the most difficult parameter to estimate because it requires high latitude electron density, ion drift, and neutral wind maps. The energy budget is important because during magnetic storms, the high latitude thermosphere can have a significant impact on the thermosphere global circulation.

In the middle latitudes the thermospheric meridional winds can push the ionosphere upward or downward depending on if the wind is poleward or equatorward. Without knowing the thermosphere wind, it is impossible to understand the mid-latitude ionosphere.

In the equatorial region the thermospheric wind drives the electrodynamics, which has a great impact on the equatorial ionosphere anomaly. Thermospheric winds affect the Rayleigh Taylor instability which is responsible for the equatorial spread F or plasma bubbles. Plasma bubbles are a major space weather phenomenon, which affects communication in the lower latitudes. Hence, thermospheric wind is a key parameter for equatorial aeronomy and space weather research.

1.3 Current Thermospheric Wind Observation

In view of the great need for the thermospheric winds, the question is whether the current observation methods can meet the requirement. Here we offer a brief review of the current methods. There are two major methods to measure the winds, one is from the ground and another is from satellite. The satellite method includes the in-situ and remote sensing technologies. There is also a NASA funded balloon borne wind instrument to measure day and night thermospheric winds called HIWIND (High altitude Interferometer WIND experiment), which is nearly ready for its maiden flight in 2011. Both ground based and balloon borne instruments are for localized measurements, which are crucial for specific regions. However, since we are mostly focusing on the need for global wind fields, we will describe only past and current satellite measurements.

1.3.1 Remote Sensing

The Dynamics Explorer 2 (DE-2) Fabry-Perot interferometer was the first spaceborne FPI for thermospheric winds measurement (Hays et al. 1981). It measures the thermospheric winds by limb scanning the O 630 nm emission. It marked a milestone for the thermospheric wind measurement from ground based instrument with limited view to a spaceborne instrument with a global view. The next spaceborne wind instruments were HRDI and WINDII on the UARS satellite (Hays et al., 1993; Shepherd et al. 1993). HRDI was mainly for the mesospheric and stratospheric winds. WINDII used a Michelson interferometer to measure the Doppler shift in the O 557.7 nm airglow emission. The most recent spaceborne Fabry-Perot interferometer is TIDI on the TIMED satellite, which was designed to measure the O 630 nm and day time 732 nm emissions. Unfortunately, due to a light leak, that capability was not realized (Killeen et al., 1999).

1.3.2 In Situ Wind Measurements

The DE-2 Wind And Temperature Spectrometer (WATS) was designed to measure the concentration, kinetic temperature, and motion (three mutually perpendicular components of the wind) of the neutral particles (Spencer et al., 1981). The quadrupole mass spectrometer was the principal sensor for the instrument. WATS measured the zonal and vertical components of the wind.

The recent CNOFS satellite has an in-situ wind instrument (Earle et al., 2007). The Neutral Wind Meter (NWM) instrument has two sensors. Ram Wind sensor measures the ram component of the neutral wind. The cross track sensor provides the arrival angle of the neutral wind. The thermospheric density has a great impact on NWM measurements.

1.3.3 Limitation of Current Satellite Measurements

The deficiency with the current and past spaceborne wind measurement lies with the low orbit of the spacecraft (~650 km). A low orbit allows a limb scan instrument to have a relatively high vertical and horizontal resolution, which is needed for lower thermosphere and mesosphere observations. Consequently, limb scan instruments usually have no more than two measurement tracks along the satellite track. In situ measurements have only one track. These measurement tracks are not far apart (~2 hr in local time). It takes 90 minutes to orbit the Earth for a LEO satellite.

A LEO satellite has to balance local time and latitudinal coverage. A high inclination angle LEO satellite can cover the entire earth during a day. However, this kind of coverage can only provide an asynoptic wind pattern. A low inclination orbit satellite (e.g., CNOFS) can have a good local time coverage but with a limited latitudinal range.

Hence in order to examine the thermospheric winds over all local times with DE-2 satellite observations, an average over many days is needed. That has greatly reduced the temporal resolution of the data. Given that the thermosphere is a very dynamic region, statistical analysis could not capture the fast temporal resolution features. Low temporal resolution data bring great uncertainties in joule heating calculation.

1.4 GAIL Instrument

Obviously a new way to observe the thermosphere is urgently needed. Here

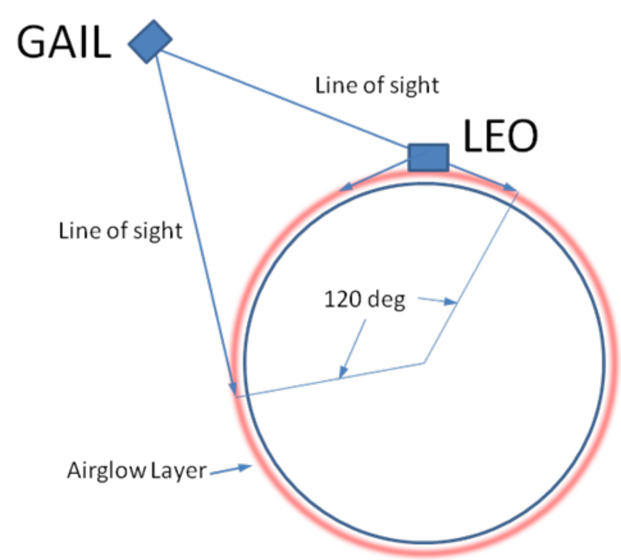

Figure 1 GAIL viewing Geometry

we propose a new satellite observation at an altitude of 6500 km, which will revolutionize the way we see the thermosphere. The GAIL (Global Airglow Interferometer Limb-scanner) instrument will be a limb scan Fabry-Perot interferometer for measuring thermospheric winds by monitoring the wind induced Doppler shift in the thermosphere O 630 nm emission. By mounting on a high orbiting satellite, GAIL can limb scan a much larger area with a larger local time separation. Figure 1 shows the comparison between the viewing geometries of GAIL with a LEO instrument. We can see that GAIL can limb scan two tangent points that are 120 deg apart (~8 hours in local time). In the LEO case, the limb scan tangent points are much closer meaning small separation in local time. By having 16 viewing directions, GAIL can have 8 measurement tracks (four on each side of the satellite) to cover a local time range of ~ 8 hours. If we count the ascending and descending nodes (separated by 12 hours) GAIL will have 16-hour local time coverage in one orbit. Figure 2 shows the 16 viewing directions and foot prints of GAIL sampling points. As the satellite moves forward, the forward looking sampling points can be paired with backward viewing sampling points after the satellite moves a certain distance to form vector winds. The paring viewing directions are plotted in the same colors. We did not show all the sampling points along the satellite track, which should have a much higher density so pairing up of viewing samples at a close proximity will not be a problem. The pairing time difference should range from 20 min to 1.4 hour.

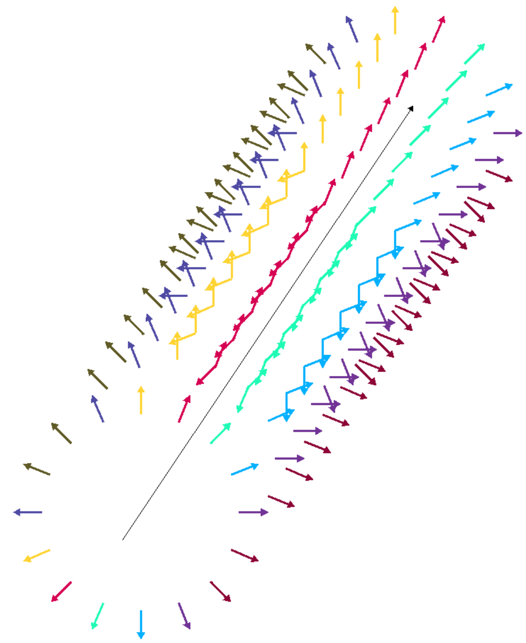

Figure 2 GAIL viewing directions and pairing.

If we use a 45 deg inclination angle, then we should have coverage of the two polar caps for every orbit. In a day, we should pass each polar cap six times. Figure 3 shows the three views of GAIL sampling points during one orbit. Figure 3a is at the Asian sector equator. Figure 3b is for the southern Pacific and Antarctica. Figure 3c is a global view in latitude and longitude.

Figure 4 is similar to Figure 3c but shows the latitude and local time coverage during one orbit. At low latitudes, we should have complete 24 hour local coverage in a 4-hour orbit. What is so special about GAIL is that it can offer nearly synoptic data set with one orbit, because of its large

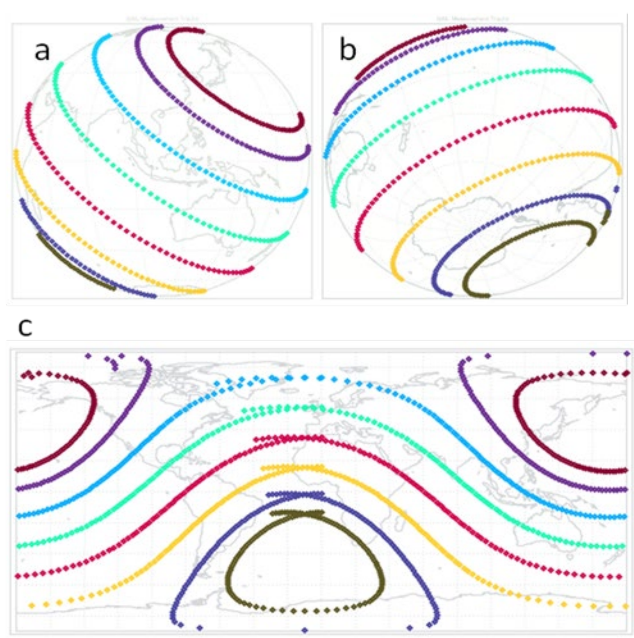

Figure 3 GAIL sampling tracks during one orbit

local time coverage.

In addition to the thermospheric neutral wind measurements, GAIL may be able to measure the ion drift by monitoring the 732 nm emission from O+ during daytime. Hence GAIL can provide both neutral wind and ion drift map globally. That makes GAIL a powerful tool to study the ion-neutral interaction globally.

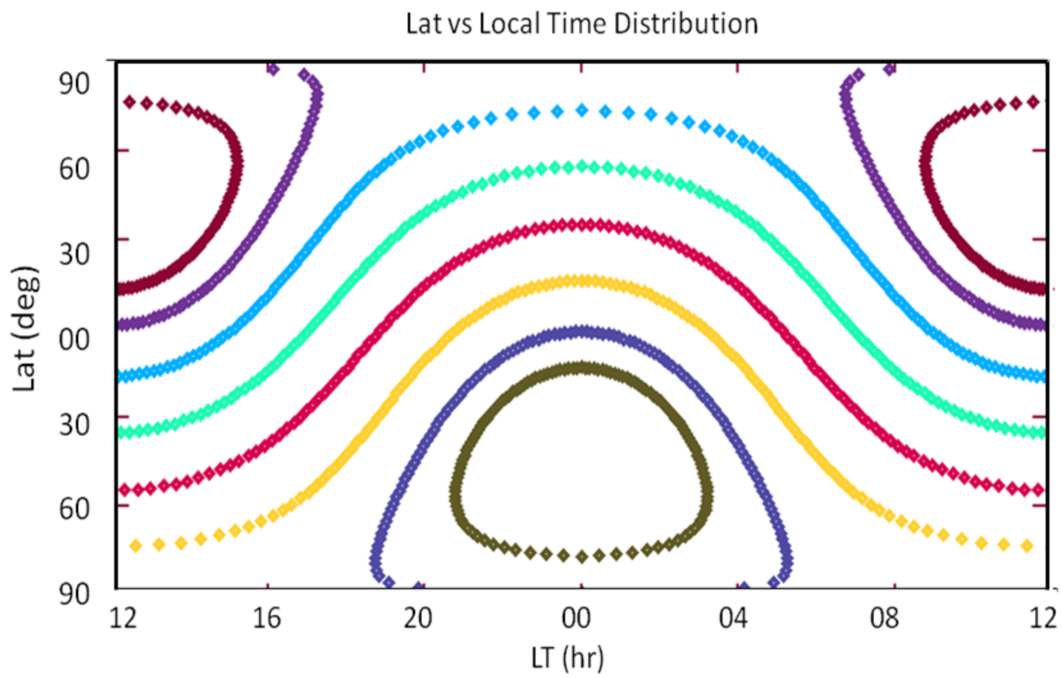

Figure 4 GAIL sampling tracks latitude and local time distribution

1.5 Issues Associated with High Orbits

The high orbiting satellite will be 11000 km away from the limb scan tangent point, which is 5 times further away compared to the LEO TIMED TIDI instrument viewing geometry. To assess the impact of this longer distance, we compare the existing LEO limb-scanner TIMED TIDI instrument with GAIL. In the case of TIDI, the FOV is 0.05 x 2.5 deg, which corresponds 2 x 100 km at the tangent point. The same FOV at a higher altitude will view an area of 10 x 500 km at the tangent point. This FOV is too large for the lower thermosphere and mesosphere where the scale height is about 7 km. However, for the upper thermosphere, this FOV is not a problem. The vertical scale in the thermosphere is about 50 km. Hence we can even increase the vertical FOV to 0.25 x 2.5 deg (50 x 500 km). The increase in the vertical field of view will increase the signal to the instrument by a factor of 5. With this FOV, the GAIL instrument can achieve a wind error of 5 m/s with 2 second integration time. That should be sufficient for the majority of dynamics studies of the thermosphere.

A high altitude orbit will also encounter the radiation belt. Hence, additional shields have to be added to protect the instrument electronics and detectors. Optical sensors will be affected even with more shields. However, with double samples for each measurement, we should be able to filter the charge particle strikes on CCD detectors.

1.6 Cost

With a reasonable amount of investment, we should be able to achieve this goal. The high altitude orbit satellite approach is cheaper than having multiple LEO satellites. We estimate the cost for GAIL will be about 100 million dollar for the instrument. Here we only need one highly stabilized platform. We will have four times the viewing directions compared to TIDI instrument. The development cost will not be quadrupled since most of the components are the same. We propose to have four separate etalons and each will handle four viewing directions. We can have a single calibration source for the four etalons.

2. Relevance to NASA Road Map priorities

We have mentioned earlier that the GAIL instrument wind measurement is indispensable to address the ion-neutral interaction between the thermosphere and the ionosphere. In addition, the NASA Heliophysics 2009/2010 roadmap has other focus areas that will require global thermospheric winds.

The research focus area for "Understand the nature of our home in Space" has two topics will be most relevant:
H2. Understand changes in the Earth's magnetosphere, ionosphere, and upper atmosphere to enable specification, prediction, and mitigation of their effects.
H3. Understand the role of the Sun and its variability in driving change in the Earth's atmosphere.

Another road map focus area that can be benefited from GAIL observation is "Safeguard the Journey of exploration"
J4. Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

In all these focus areas, the thermosphere is one of the key elements. The GAIL instrument can make a real difference.

Given the impact of the thermosphere on the ionosphere, a good thermosphere model with sufficient data for assimilation will have a great impact on space weather forecast capability. A strong space weather forecasting tool will have a tremendous economic and societal impact with ever growing usage of communication and navigation electronics. We envision making GAIL thermosphere data available in real time for space weather forecast operation.

GAIL is a cost effective way to achieve a global coverage of the thermospheric winds. By grouping multi-direction measurements into one high orbit spacecraft, it greatly reduces the cost. Fabry-Perot interferometer is a very mature technology, which has been flown on many missions.

Human resources for such technology are still available. However, if we wait for another decade, we will lose much of our heritage.

A high orbit satellite is also good for global UV imaging, which allows nearly simultaneous viewing of aurora, equatorial ionosphere anomaly region, and plasma bubbles. GAIL combined with such an imaging instrument would form a strong instrument package.

3. Conclusions

Lack of the thermospheric winds has hampered the progress on thermospheric and ionosphere coupling studies and severely impacted space weather forecast capabilities. The GAIL instrument will provide a truly global coverage in much short time scales (in hours, not days). It will transform how we study the thermosphere and ionosphere system. It is an instrument we must have in a new decade.

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White Paper on: Experiments to Demonstrate Solar and Astrophysical Dynamos

Stirling A. Colgate, LANL, Nov. 12, 2010

Summary:
A significant fraction of solar physics depends upon the existence of magnetic fields in the sun as well in other stars, yet so far there has been no laboratory demonstration of a dynamo in unconstrained flow in a conducting fluid. A similar situation exists for the cosmos. Indeed the experiments based on the early ansatz that turbulence alone would make a dynamo have all led to the recognition that turbulence leads primarily to enhanced resistive diffusion and not, by itself, to a dynamo. Only flows, constrained by rigid walls have shown dynamo gain. It is only through experiments, not theory or modeling that this understanding has emerged. At NMIMT we have demonstrated that large scale coherent flows and natural stability, not turbulence, has led to large gain, x8, in one of the two orthogonal motions necessary for dynamo gain. At Madison the addition of a midplane rigid wall baffle to reduce unconstrained shear turbulence has had a similar, x4, positive effect in Dudley-James flow. We therefore believe that a continuing program seeking dynamo gain through laboratory experiments is vital to discovering the truth about dynamo physics.

The purpose of this recommended research is to explore whether a solar or astrophysical dynamo is created primarily by coherent motions as opposed to turbulent motions. This question needs to be addressed in many experiments, because modeling and theory have failed, so far, relative to experiment, in giving us the answer.

The laboratory $\alpha-\Omega$ dynamo at NMIMT is based upon coherent, stable fluid motions and now has a successful result of high shear gain, the Ω phase, in a stable, Couette shear flow of low turbulence in liquid sodium. One expects low turbulence in shear flow in three circumstances of astrophysics: 1) Keplerian accretion disks; (The years of theoretical and computational effort to prove a robust source of turbulence in accretion disks is proof enough that a stable gradient of angular momentum is a significant barrier to turbulence.) 2) When the fluid Reynolds number is small as in the cores of planets one expects sufficient viscosity to damp the turbulent eddies. 3) At the base of the convection zone of stars we expect a similar stabilization due to the gradient of entropy. This latter needs to be demonstrated by calculations. The ability of viscous damping, a gradient of angular momentum, and a gradient of entropy to damp eddies should be demonstrated in the laboratory.

The α-phase of an astrophysical dynamo, the source of the helicity, is conceptually the most difficult to imagine. By comparison the Ω–phase, the coherent rotational shear in an accretion disk, is almost a no-brainer. The α-phase or coherent helicity has been suggested as originating in a naturally occurring fluid deformation, i.e., plumes in a rotating frame. The helicity is the deformation of the conducting fluid that captures a fraction of the enhanced toroidal flux from the α-phase coherent winding and transforms a fraction back into orthogonal, poloidal flux of one sign and one geometry such that subsequent α-phase coherent winding amplifies it again creating more toroidal flux. Coherence in this case means the same twist of poloidal flux, a quarter turn, and a translation of the flux out of the symmetry plane every time.

This would seem to be a tall order, but surprisingly nature seems to do this to a buoyant plume of matter rising relative to the plane of symmetry in a rotating frame. One observes a typical smoke plume from a smoke stack rising in a turbulent fashion, but when a "puff" of gas or smoke is ejected from an orifice, it travels several diameters and expands transversely before mixing with the background gas. This transverse expansion causes an increase in the moment of inertia of the plume matter so that transiently it rotates slower than the frame. It is the transient conservation of angular momentum that causes the plume to rotate relative to the frame, as observed in water simulation experiments. Surprisingly the combination of transient rotation and mixing limits the effective rotation to about ¼ turn, the ideal to transform toroidal flux into poloidal flux. Meanwhile the plume has risen relative to the plane of symmetry. This is the ideal helicity deformation for a coherent dynamo. In a star or the sun, the analysis by Chandrasekar of the Rayleigh-Taylor growth in a gradient of unstable buoyancy (density) predicts the fastest growing mode is not the smallest wave length, but instead a wave length corresponding to the logarithmic gradient of the buoyancy or roughly the density scale height. This large scale is then the expected scale of the first plumes to rise at the base of the convective zone. The combination of scale and finite plume rotation make this natural deformation an ideal source of helicity to complete the solar dynamo cycle.

Finally there is one observation that suggests consistency with this coherent model. The back-reaction limit of such a dynamo would most likely be the stress of the magnetic fields altering the dynamics of the plumes. The dynamic stress of these plumes is the stress of convection or: solar luminosity = area * rho $v^3/2$. Then $B^2/ 8\pi$ = rho v^2 with rho ~ 0.1g/cm^2. Solving for B ~ 10,000 gauss. The largest sun spots show a core of order B ~ 5,000 gauss. It there has been some expansion in the rise from the convective zone, then these values are approximately consistent.

The simulation of such a stellar dynamo is still a major challenge to computational science because of the difficulty of modeling turbulence and the necessary immense range of scales. The one simulation of such a dynamo using a vector potential code approximated the plumes as right circular cylinders without the typical structure of a pulsed plume. The uncertainty of simulations of turbulence will justify experimental truth for some time to come.

Research To Operations (R2O) Activities, a Natural Conclusion of Research

Eduardo A. Araujo-Pradere

Abstract: *The transitions of academic models from research to operations have been recognized as an important and needed element of the research process that would improve the inefficient knowledge transfer currently existing in Space Weather. These activities require an organizational structure and a clear financial commitment from the interested institutions, barely existing today* --

In order to satisfy current and future societal and technological needs, a clear path from research to operations should be established. However, there is no such a community supported path, and not even clear funding for transition and transition-related activities. As the Assessment Report on the National Space Weather Program (NSWP) (http://www.nswp.gov/nswp_acreport0706.pdf) found: ***"****There is an absence of suitable connection for "academia-to-operations" knowledge transfer and for the transition of research to operations in general".*

The definition of a standard process for defining metrics, model selection requirements, and of a transition process should involve the wider community, academia, government and private enterprise, along with the users or customers of the final products. Reaching, in this way, a broad acceptance of the general process, would facilitate the selection and transition activities. With this goal in mind, a series of community and interagency workshops should be organized to initiate the communication on this topic and to establish a working relationship that would further the desired community support.

In this context, it is useful to establish a clear distinction between "academic" and "operational" real-time models, and requirements for transition of academic models to operations. "Academic" models are assumed to be intended for the understanding of physical processes, cause-effect relations, etc. Academic models are not designed for production of customer-oriented products, even if they have been implemented as real-time models. "Operational" models offer products on which third parties rely to conduct their businesses. An operational product requires validation, full documentation, reliability, and some degree of standardization (among other requirements), whereas an academic model does not. An academic model serves the purposes of the scientists, and can be adjusted at will to fit the researcher needs. Academic models, however, can be transitioned into operations, and the process to do it, the transition process, includes the fulfillment of a series of requirements discussed by Araujo-Pradere (2009).

Even before a model is selected for transition to operations, a selection process should be defined in such a way that all the academic models with results similar to what is needed are considered. A good starting point is the need for a particular product, which is often clearly expressed by interested customers, and, if published to the broader community, could become the metric against which models can be designed and tested. As a part of the selection process, and to be refined after a selection is made, an important step should be a careful verification -benchmarking, standard test suites, comparison with first principle simulations, etc.- and validation -comparison studies of modeled and measured time series in global sense (prediction efficiencies, distribution functions) and in dichotomous sense- process (the frequently mentioned V&V). During the transition process, the behavior of the model during failures and specific events must be characterized, along with the uncertainties and errors inherent to the model. A transitioned model must be accompanied by full documentation, including a description of input/output and "how-to", of physics and methods, results of the V&V process, etc.

Generally, the transition process should consider the frequently intense process of training the users to work with the model output, from the forecasters (in the case of the Space Weather Prediction Center) to private companies interested in the use of the model.

The activities described here are essential for establishing an efficient transition process. These activities require a level of financial support and organizational structure scarcely existing now. The organization of a series of community and interagency workshops will create the right space for discussions and collaborations, and will convey a message to funding agencies to start thinking of R2O (as well as O2R) processes as a fundamental part of our scientific labor, and therefore, worth to be supported in all extension.