



EXPLORESCIENCE

*Heliophysics Research at NASA relevant
to Plasma Physics*

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Universal Aspects of Magnetized Cosmic Plasmas

Creation and Annihilation of Magnetic Fields

- Dynamos
- Diffusion
- Dissipation
- Reconnection

Energetic Particle Acceleration

- Shock Acceleration
- Electric Field Acceleration
- Stochastic Acceleration

Formation of Structures and Transients

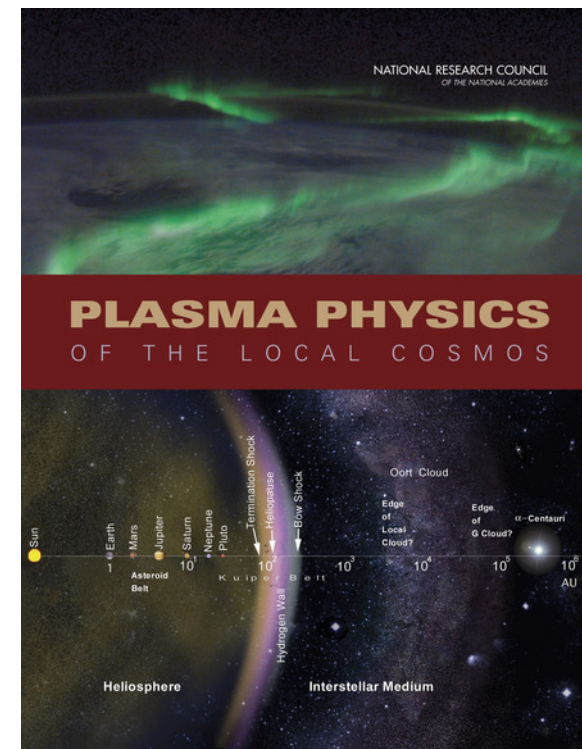
- Collisionless Shocks
- Current Sheets
- Cellular Structures
- Flux Ropes-Filaments
- Turbulence

Plasma Interactions

- Electromagnetic
- Flow-Object
- Plasma-Neutral
- Radiation-Plasma

Explosive Energy Conversion

- Solar (Stellar) Flares
- CMEs
- Substorms



Source: [Plasma Physics of the Local Cosmos](#); National Academy of Sciences 2004; DOI 10.17226/10993.

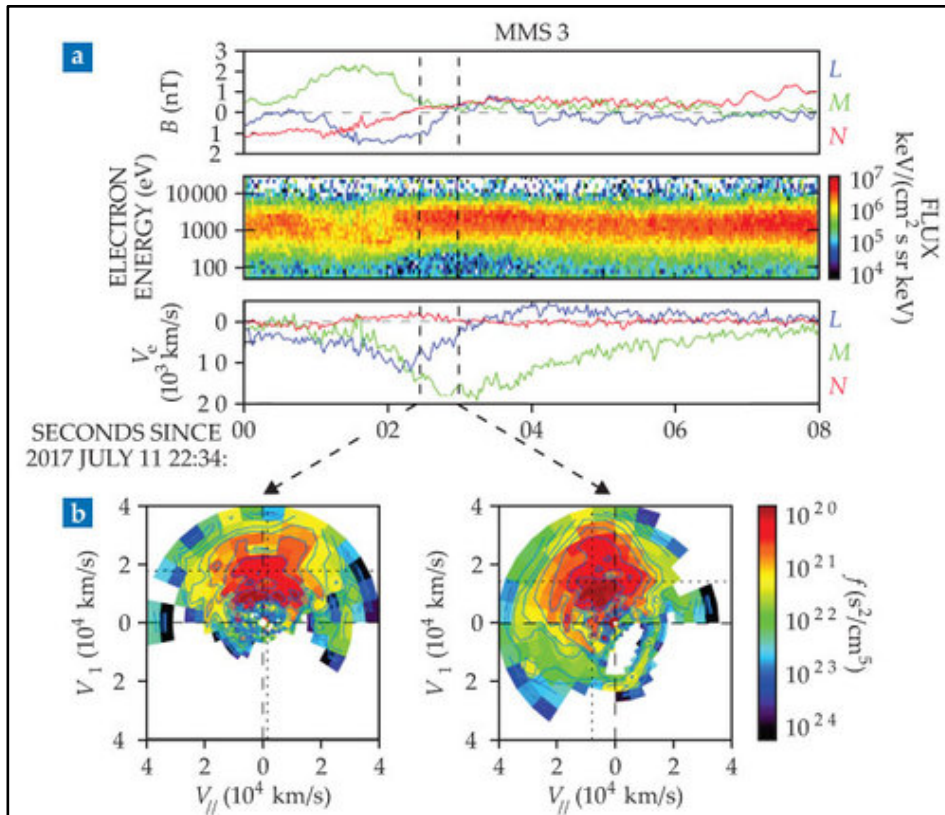
Heliophysics System Observatory

- 18 Operating Missions with 26 Spacecraft
- 3 Missions in Development
- 1 Mission in Formulation



	HSO	Magnetic Fields	Structures & Transients	Plasma Interactions	Explosive Energy Conversion	Particle Acceleration
SOLAR	Hinode (Solar-B)	S		P		P
	IRIS		P	P	P	P
	SDO	P		P	P	P
	SOHO		P	P		
	STEREO	S	P		P	
	PSP		P	P	P	P
	ACE		P	P		P
	IBEX			P		P
	Voyager (1 & 2)		P			
	WIND		P	P		
HELIO-SPHERE	ARTEMIS		P	P		
	Geotail	S	P	P	P	P
	MMS	P	P	P		P
	THEMIS	S	P		P	P
	Van Allen Probes			P		
ITM	AIM		P	P		
	GOLD		P	P	P: Primary Science S: Secondary Science	
	TIMED			P		

Magnetospheric Multiscale (MMS) Mission



Observed reconnection event: MMS observations (a) the magnetic field B (top), electron spectrogram (middle), and electron velocity V_e (bottom) in the electron diffusion region of a magnetic reconnection event on July 11, 2017. During reconnection, the magnetic field vanished and the electron bulk velocity peaked at 15,000 km/s. (b) Crescent-shaped structures persisted in the electron velocity distribution during reconnection. Plots of phase-space density as a function of velocity components $V_{\perp}$, in the direction perpendicular to the magnetic field, and $V_{\parallel}$, parallel to the magnetic field. **Published in:** Rachel Berkowitz, *Physics Today*, 72, 20-23 (2019), DOI: 10.1063/PT.3.4129
Copyright © 2019 American Institute of Physics

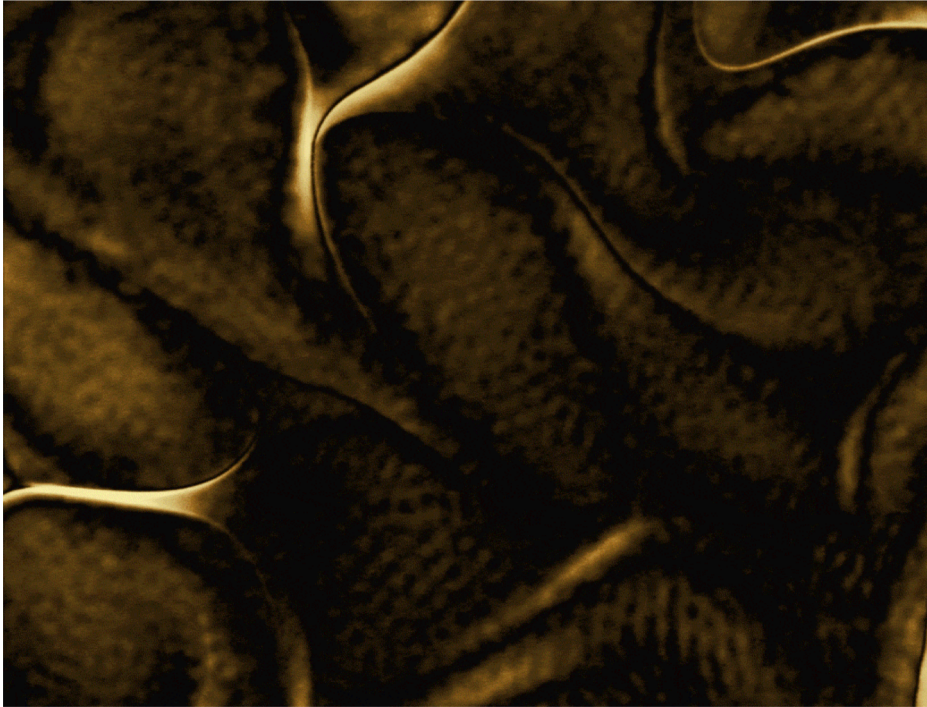
MMS utilizes four identical spacecraft orbiting in a tetrahedral formation to observe magnetic reconnection events. Such transient space plasma phenomena are triggered by the reconfiguration of oppositely aligned magnetic field lines. The MMS constellation resolves such 3-dimensional events as bi-directional jets of high speed electrons seen not only along the dayside magnetosphere (asymmetrically), but also in the Earth's magnetotail, the nightside magnetosphere (symmetrically).

Mission Phase 1: MMS examined reconnection sites at the mid-latitude dayside magnetopause where the interplanetary magnetic field (IMF) triggers reconnection.

Mission Phase 2: MMS constellation examined reconnection in the nightside magnetotail where the energy release triggers magnetospheric substorms.

Current Science Campaign (beginning Feb 15, 2019): One month campaign will enhance understanding of plasma turbulence in the solar wind and characterize turbulent energy flow. Utilizing 6 different separation lengths ($\sim 20 \text{ km}$ to $\sim 200 \text{ km}$) allows correlation lengths normal to solar wind velocity

MMS: Magnetic Reconnection

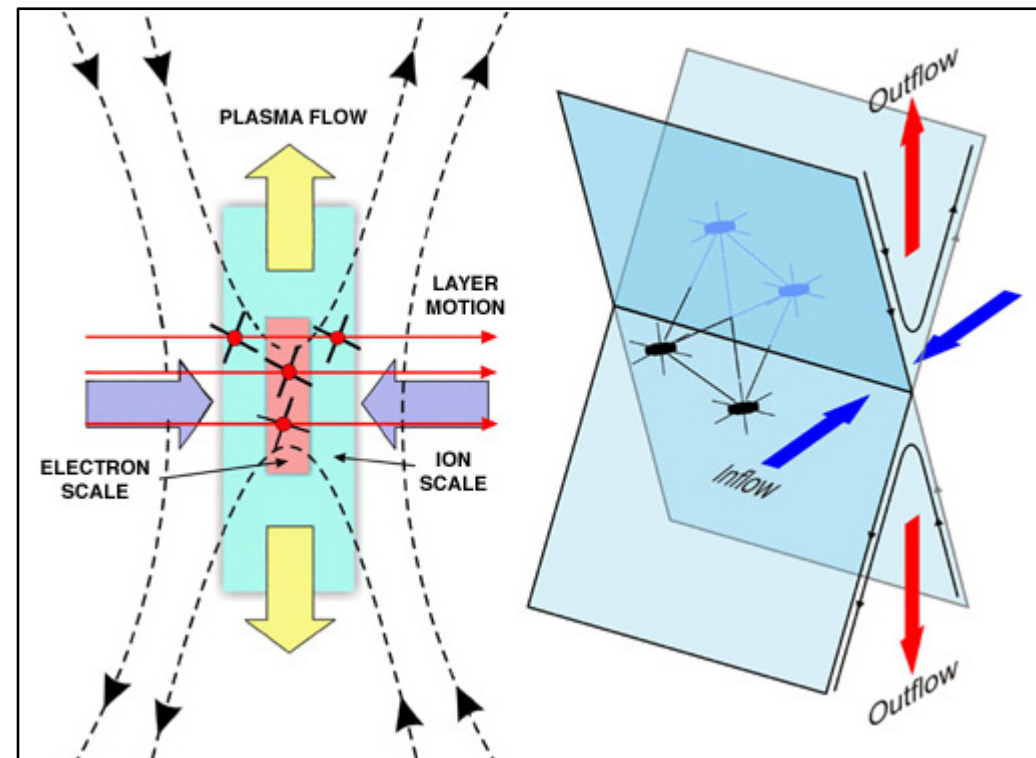


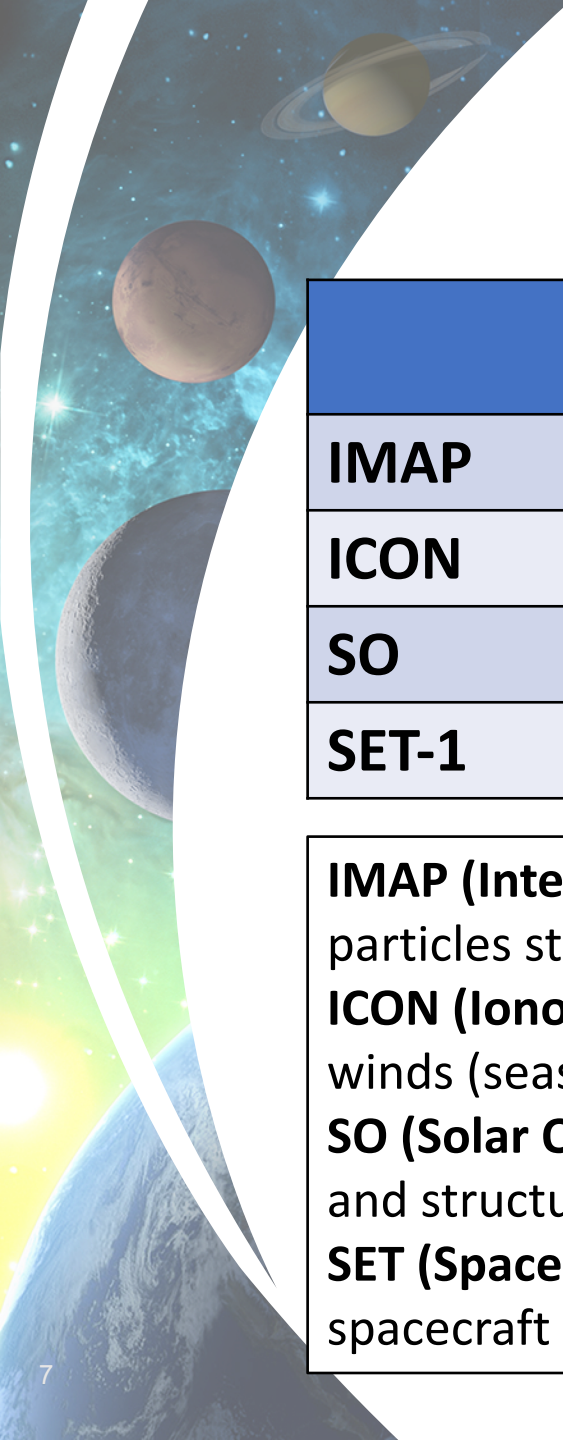
Video: Microscale magnetic turbulence. Flashes indicate magnetic reconnection triggered when field lines cross and intense electric currents (bright regions) are formed.

Credits: NASA's Goddard Space Flight Center's Conceptual Image Lab/Lisa Poje; Simulations by: Colby Haggerty (University of Chicago), Ashley Michini (University of Pennsylvania), Tulasi Parashar (University of Delaware)

Launched in March 2015 MMS can resolve microscale structures in 3 dimensions which had eluded previous science investigations utilizing only single point measurements.

Below: Illustrations showing spacecraft residing within the diffusion region (left) and a 3D rendering of a reconnection site (right).





Missions in Formulation/Implementation

	Magnetic Fields	Structures & Transients	Plasma Interactions	Energy Conversion	Particle Acceleration
IMAP		X	X		X
ICON		X	X		
SO		X	X	X	X
SET-1			X		

IMAP (Interstellar Mapping and Acceleration Probe): Sample, analyze, and map interstellar particles streaming to Earth.

ICON (Ionospheric Connection Explorer): Study neutral particle and ion transport by giant winds (seasonal, diurnal, and radiation impacts).

SO (Solar Orbiter): Study inner heliosphere and how it is affected solar activity (source regions and structures) on the Sun's surface.

SET (Space Environment Testbed): Study mechanisms of space environment to improve spacecraft design protocols.

Laboratory Studies (1 of 2)

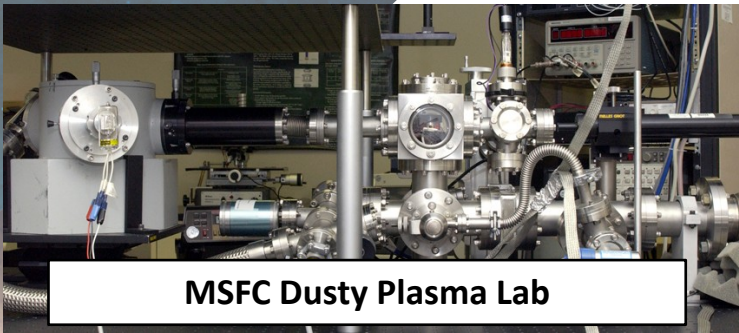


Princeton Plasma Physics Laboratory (PPPL) – DOE Operated Facility
UCLA Large Plasma Device (LAPD).

NASA supported facilities host plasma chambers that are utilized in the study of reconnection, plasma turbulence, wave-particle interactions, and particle acceleration.

- PPPL - Magnetic Reconnection Experiment (MRX): Studies processes generating astrophysical events such as aurora, solar flares, and geomagnetic storms
- LAPD - Operational procedures foster exchange of technical information across diverse areas of research (e.g. fusion, space investigations, laser-plasm interactions, plasma applications).

Laboratory Studies (2 of 2)

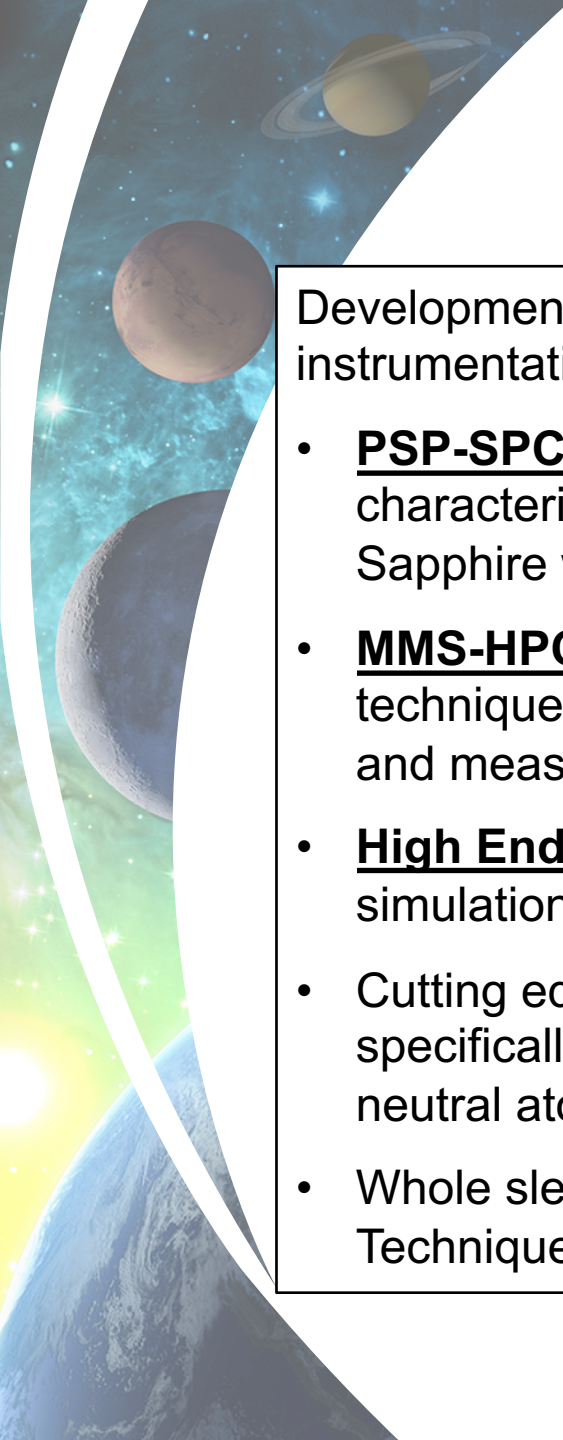


Marshall Space Flight Center (NASA-MSFC)

Institute for Modeling Plasma, Atmospheres, and Cosmic Dust (IMPACT) - located at CU-Laboratory for Atmospheric and Space Physics (LASP)

NASA supported facilities which investigate dusty plasmas in space environments.

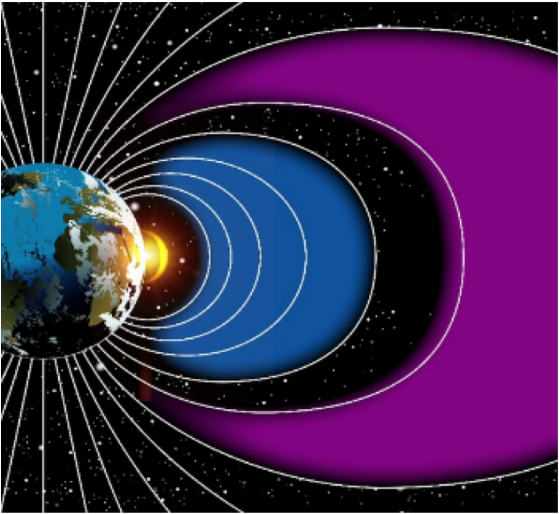
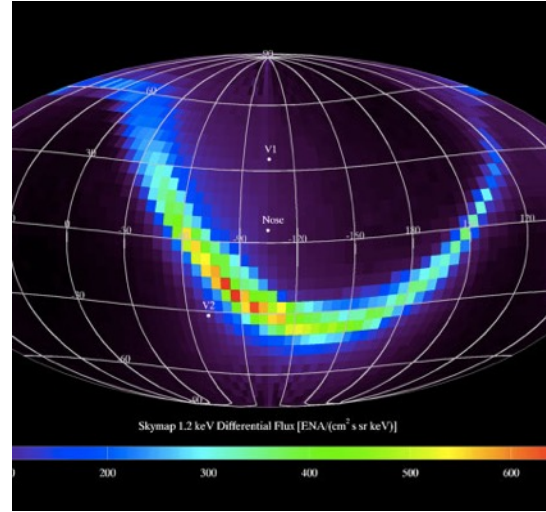
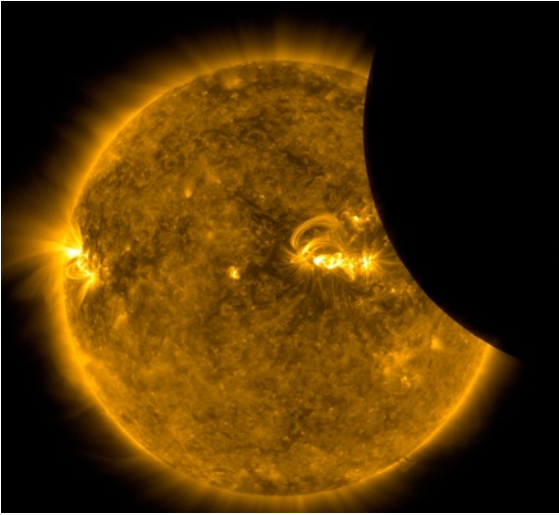
- MSFC – Studies interstellar gas/dust and role in the cosmic dust cycle. Electrodynamic balance (EDB) used to investigate individual grains $\leq$ micron-size dust in simulated space environment.
- IMPACT – Interdisciplinary program investigating the physical processes governing dusty plasmas including issues necessary for ensuring human safety and long-term usability of mechanical and optical devices on airless bodies.



Unique Advancements in Space Plasmas

Development of plasma diagnostic and measurement techniques are an inherent part of missions, instrumentation, and experimentation that have unique applications.

- **PSP-SPC (Solar Probe Cup)**: Specially designed Faraday cup that captures and analyzes characteristics of charged particles in the solar wind while exposed to the full might of Sun. Sapphire was used to electrically isolate various components.
- **MMS-HPCA (Hot Plasma Composition Analyzer)**: Employs a novel Radio Frequency (RF) technique using an imposed quadrupole resonance frequency on entrance plates to filter out ions and measure only minor plasma constituents (Oxygen and Helium).
- **High End Computing (HEC)**: Utilizes petabyte technology capabilities to handle large kinetic simulations, examine instabilities, and resolve complexities of turbulence.
- Cutting edge laboratory techniques in plasma diagnostics or instrumentation testing developed specifically to achieve overall objectives (e.g. generate very low energy ions and electrons, or neutral atom imaging for surface interactions that create plasmas and charged particles).
- Whole slew of development efforts are outlined in Geophysics Monograph - Measurement Techniques in Solar and Space Physics, Vol I and II JGR 2017



The Dawn of a New Era for Heliophysics

Heliophysics Division (HPD), in collaboration with its partners, is poised like never before to:

Strategically advance understanding of solar and space physics, make amazing discoveries

Fulfill its role for the Nation enabling advances in space weather

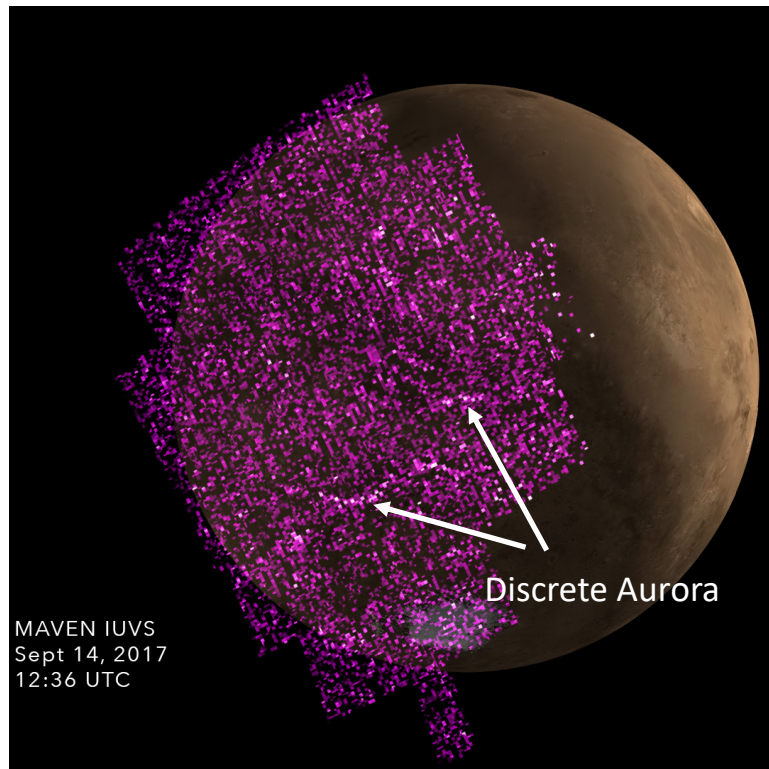
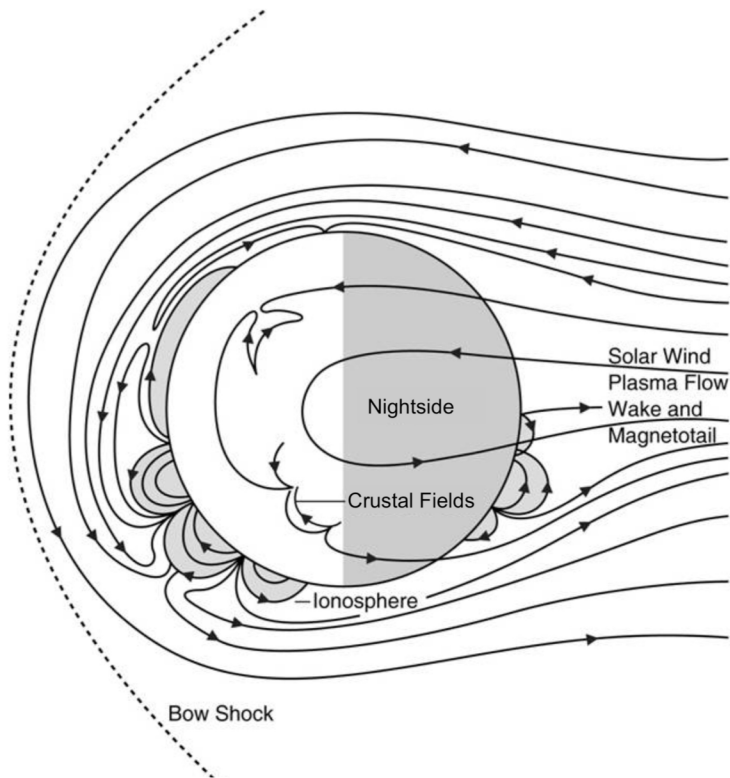
Develop the next generation of heliophysicists

Engage the public with science knowledge and citizen science

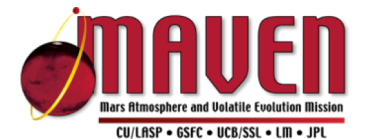


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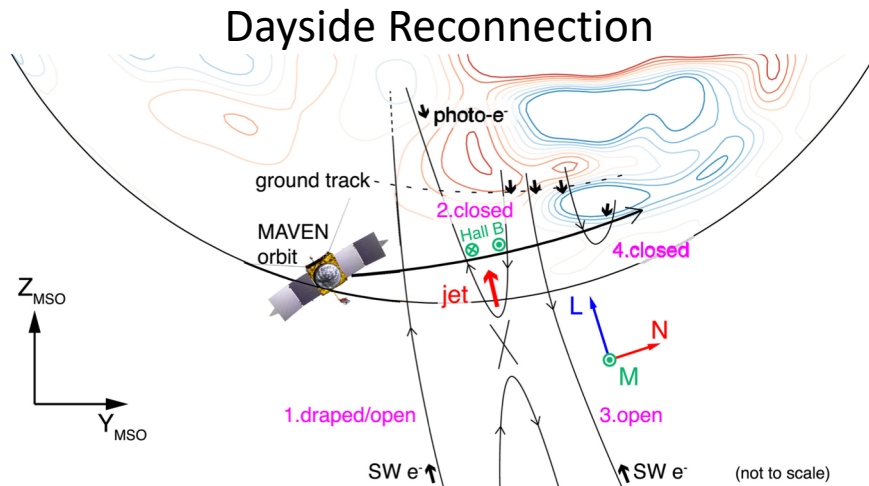
*Planetary Research at NASA relevant to
Plasma Physics*



Interaction Of Solar Wind With Crustal Remnant Magnetic Fields

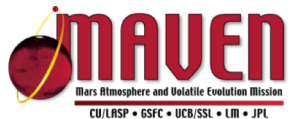


- Mars' lacks a global intrinsic magnetic field but has localized regions of crust with remnant magnetism
- Crustal fields result in magnetic field lines that can be attached to the surface/atmosphere at both ends, or attached at one end and open to the tail at the other (left)
- Configuration constantly changing via reconnection due to planetary rotation and solar-wind variability
- Solar-wind particles coming in along open field lines at magnetic cusps cause aurora (right)
- Ionospheric particles outbound along the same open field lines can result in significant loss to space

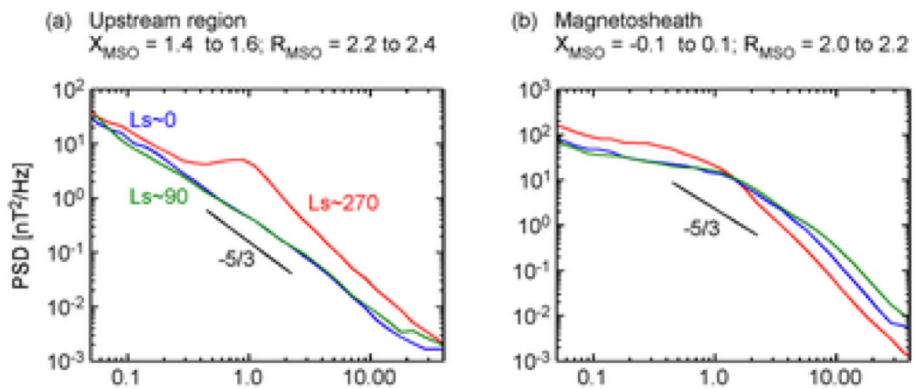


Interactions between solar wind and crustal magnetic fields lead to complex reconnection

MAVEN Is Determining Fundamental Physical Processes at Mars



Magnetic-Field Power Spectra

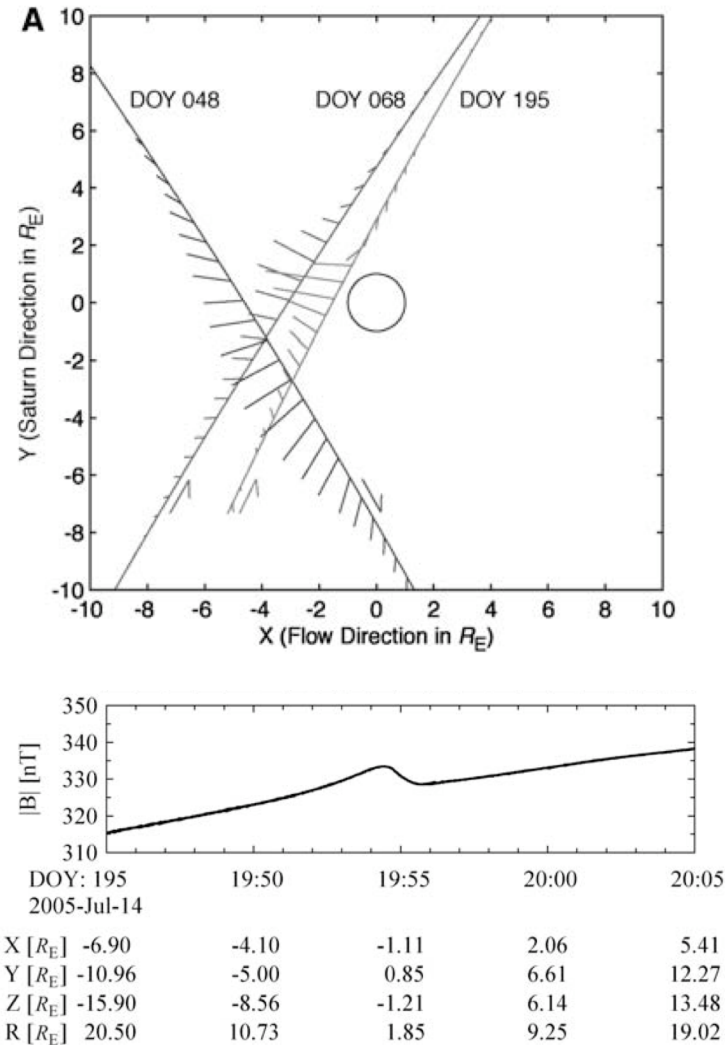
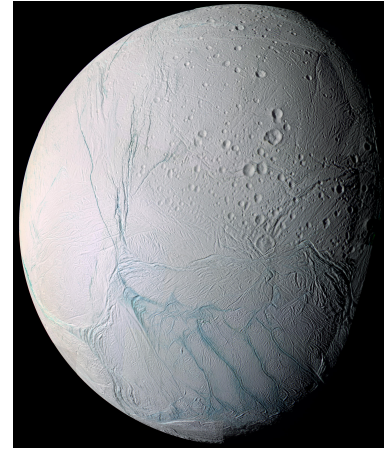


Pickup ions drive seasonally variable turbulence, indicated by the changing power spectra

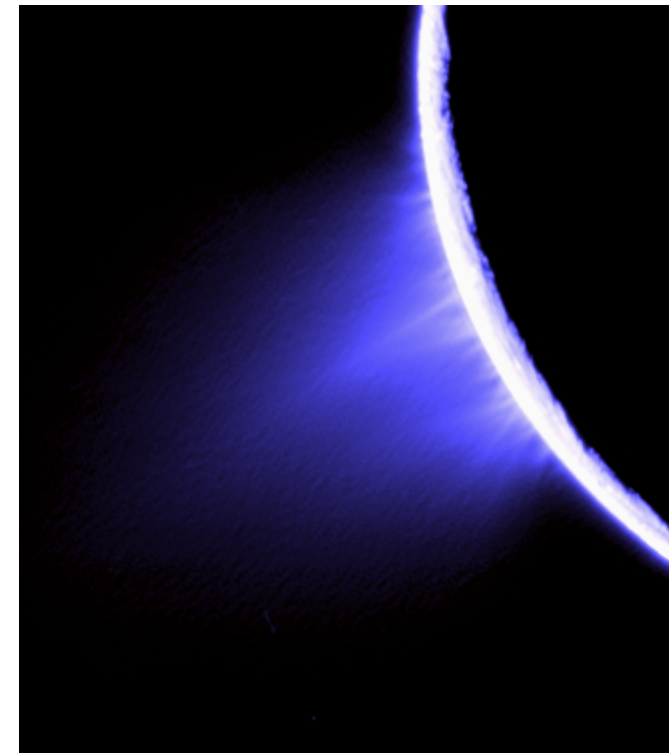
Mars is a natural laboratory for studying how fundamental plasma physical processes affect the solar-wind interaction with the Mars obstacle and its consequences at Mars

- Mars' small-scale crustal fields lead to widespread magnetic reconnection due to the changing configuration of the field lines as Mars rotates
- Pickup ions and reflected particles lead to strongly driven turbulence upstream of the bow shock and in the magnetosheath
- The small Martian system provides a unique end-member case for the study of collisionless shocks and foreshock processes

Cassini Discovers a Plume at Enceladus!



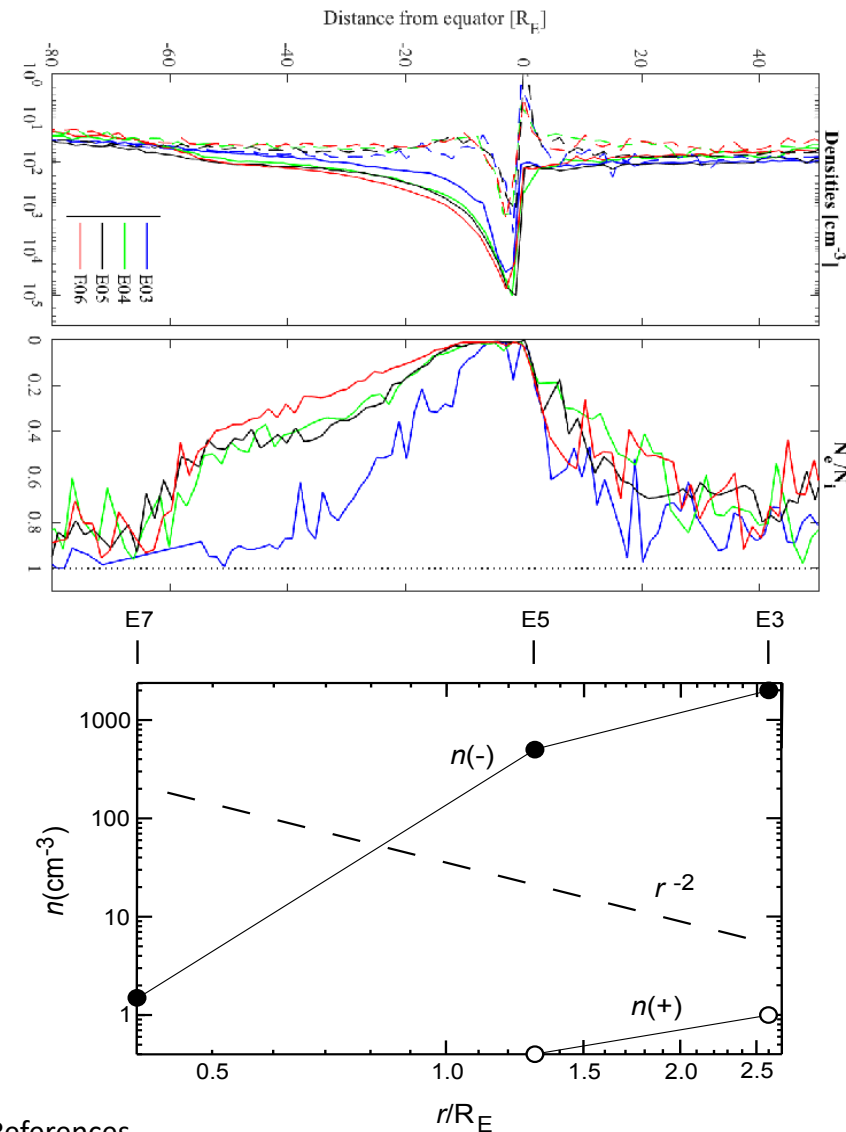
- Magnetometer measurements of the deflected magnetic field near Enceladus provide the first indication of the presence of a plume
- Enceladus was presumed inert and therefore no plume was expected
- Subsequent analysis by the the Imaging Sub-System (ISS) finds further, clear evidence of “jets” of gas and dust emanating from the south polar tiger stripes



(Dougherty *et al.*, 2006)

Enceladus' Unique Plasma Regime

- The South-Polar Plume
 - Mainly comprised of dense neutral water vapor
 - There is a cold plasma component of mainly water group ions (H_2O^+ , OH^+)
 - There are ice clusters (dust) that range in size from nanometer to sub-millimeter
- Charge Neutrality in the Plume Plasma
 - Initial measurements indicated that there was a problem with quasi-neutrality. With n_e/n_i as low as 0.01.
 - RPWS measurements showed that small water-ice grains impacted on the electric antennas in the same region as the large drop in the electron density.
 - RPWS and CAPS later showed that a dusty plasma exists in the Enceladus plume. Nanograins are largely uncharged when they emerge from the surface vents, and become increasingly (mostly negatively) charged as they move away from the surface. Nanograins carry the majority of the dust charge. **Charged dust explains the lack of electrons in the plasma.**
 - The most plausible charging mechanism is electron attachment from the dense plume plasma.
 - **Such “nanograins” had been inferred to exist in various cold, tenuous geophysical and astrophysical environments, but the close Enceladus plume encounters by Cassini offered the first (and still the only) opportunity to measure and characterize these nanograins *in situ*.**

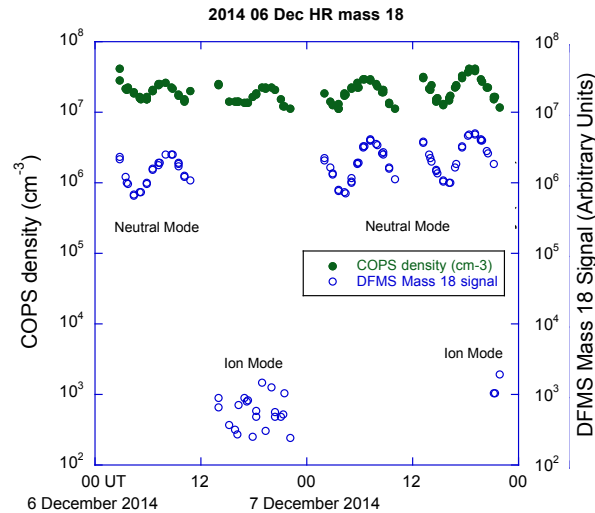


References

Coates et al., 2009, Farrell et al., 2009;
 Jones et al., 2009, Hill et al., 2012, Morooka et al., 2011,
 Meier et al., 2014, Dong et al., 2015, Meier et al., 2016,



The Environment of Comet 67P



Fuselier et al., Astronomy & Astrophysics, 2015



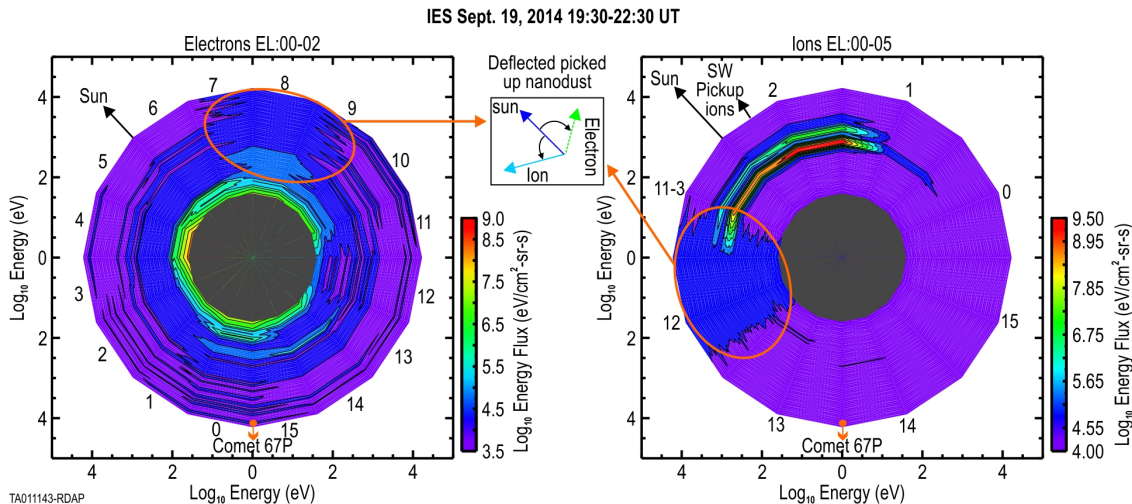
Rosetta is an ESA lead mission with several US/NASA instruments

The cometary neutral and plasma environment

- The Rosetta ROSINA instrument made measurements of the neutral and ion environment very close to comet 67P
- Neutral particles close to the comet show variations at the ~6 hour period of rotation of the comet while ion measurements do not. This is likely due to the specifics of the pick-up process
- Close to the comet (20 km) exists an interesting plasma regime where the neutral density is nearly four orders of magnitude higher than the ion density. Ion-neutral interactions in this region are extremely important

Charged Nanograins

- Comet 67P exhibits interesting effects due to the charging of dust and icy grains.
 - Grains are charged on the surface where they can levitate
 - Grains are charged in the coma where their distribution overlaps with both the neutral gas and the plasma
- The NASA supported IES instrument measurements at comet 67P for the first time simultaneously detected both positively and negatively charged nanograins!
 - Grain are observed co-located in time and space
 - This measurement has implications for dust charging models



Llera et al., IES team @ SWRI San Antonio, in preparation, 2019

Comparative Plasma-Neutral Environments

- Plasmas in planetary “magnetospheres” are frequently spatially co-located with the neutral gas from which the plasma is derived
- NASA and ESA missions have observed a range of interesting plasma-neutral environments
- Plasma Regimes of Jupiter, Saturn and Comets
 - Each of these bodies has a large source of neutrals in the “magnetosphere”
 - Neutrals are ionized and energized in situ
 - The ratio of ion density to neutral density varies widely across these different “magnetospheres” and presents an opportunity to study the different plasma/neutral regimes



Mission	Target	Neutral Source	Dominated by	Ni/Nn
JUNO	Jupiter	Io	Ions	60
Cassini	Saturn	Enceladus	Neutrals	0.1
Rosetta	Comet 67P	67P	Neutrals	0.0001



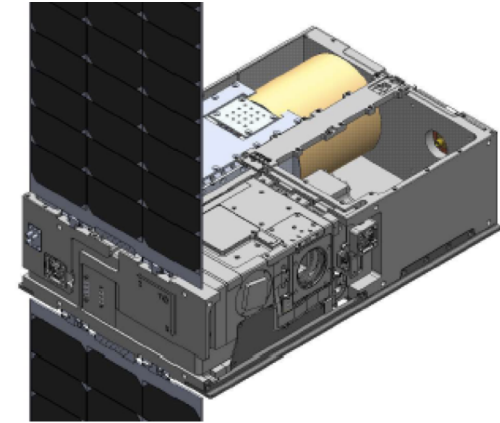
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*Astrophysics Research at NASA relevant
to Plasma Physics*

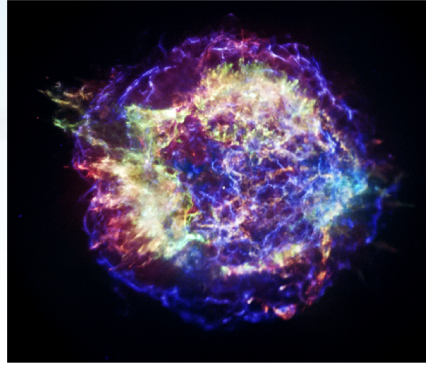
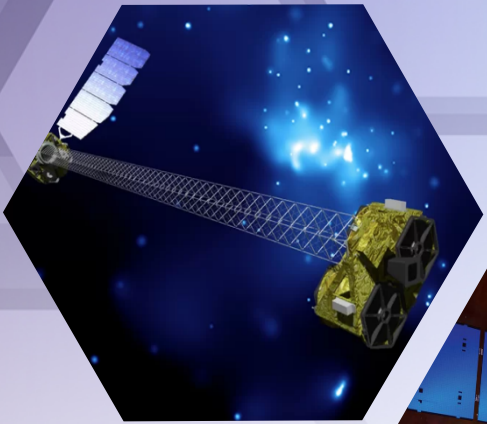
Most of the Universe is in the Plasma State



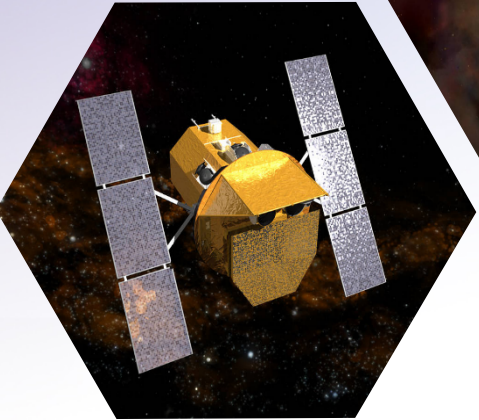
- Astrophysics Plasma Studies Subject areas, small to large:
- Star / Planet Connection
 - How does this effect exoplanet habitability?
 - Ongoing studies with Flagships, Explorers, and others
 - Upcoming dedicated studies via CubeSats (SPARCS, ASU)
 - ROSES Exoplanet Research Program (XRP) now joint across all SMD directorates
- Stellar Atmospheres
 - Ongoing studies with Flagships to Sounding Rockets (e.g., DUECE) and everything in between
- Interstellar Medium
 - Ongoing studies with Flagships to Sounding Rockets (e.g., CHESS) and everything in between
- Intergalactic Medium
 - Ongoing studies with Flagships to Balloons (e.g., FIREBALL) and everything in between
- Clusters of Galaxies
 - Largest gravitationally bound structures, IGM x-ray emitting plasma is vast majority of mass



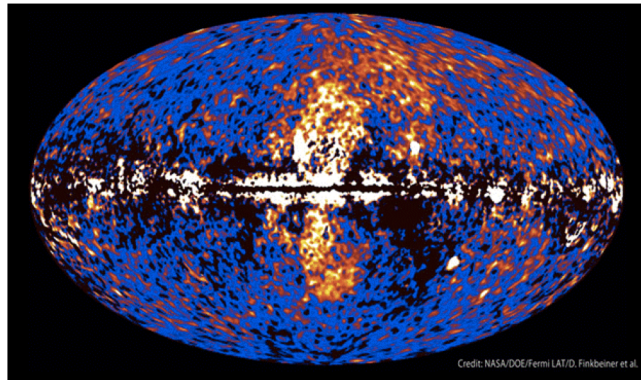
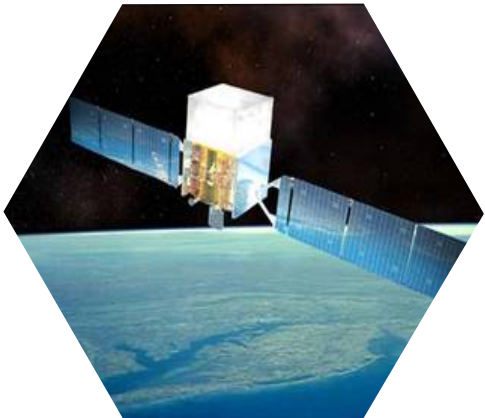
APD Missions studying Plasmas



- The temperatures of cosmic X-ray sources range from 10^6 to 10^9 degrees, and for cosmic gamma-ray sources, above 10^9 degrees. At these temperatures most matter is in plasma form (exception: collapsed objects, e.g. white dwarfs, neutron stars, black holes).



- Current APD X-ray missions: Chandra, NuStar, Swift, NICER, XMM-Newton



- Current APD gamma-ray missions: Fermi

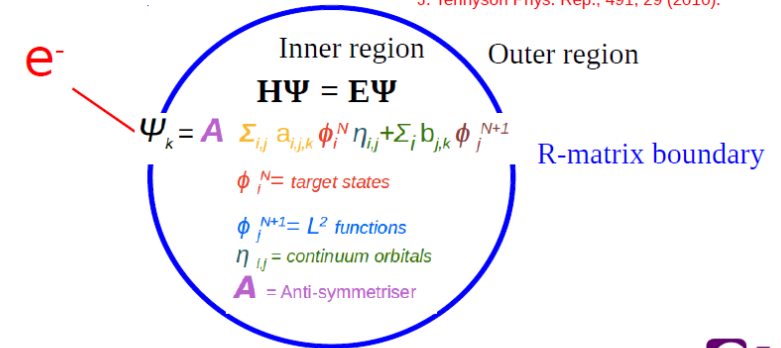


Plasma research within APD

- R&A program has two places where this is funded:
- Theory (ATP). Approximately 25% of all funded proposals deal directly with plasma physics. This is approximately \$3.6M annually

Essence of R-matrix method

J. Tennyson Phys. Rep., 491, 29 (2010).



September 14, London

(within the Fixed-Nuclei approximation)



- Laboratory Astrophysics (LA) Approximately 25% of all funded proposals deal with x-ray emissions, therefore plasmas. This is approximately \$1M annually.

