Space Plasmas: from the Origins of the Heliosphere to Solar Wind/Magnetosphere Interactions

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Our Space Plasma Environment

Sun: coronal heating,
Solar wind, flares, CMEs,
shocks, cosmic Rays (SEPs), CIRs

Planetary Magnetospheres: shocks,
radiation belts, substorms, storms, pulsations
Solar corona, wind and magnetic activity
The Solar Wind in 3D
The Heliosphere in 4D

a. Ulysses First Orbit

b. Ulysses Second Orbit

c. Ulysses Third Orbit

SWOOPS
Speed [km s\(^{-1}\)]

- Outward IMF
- Inward IMF

- Smoothed Sunspot Number

Current Sheet Tilt [deg]
WSO Radial
• Sun – Earth plasma interactions:
  - magnetospheric energy and particle input
  - foreshock phenomena
• Magnetic to particle energy conversion in the magnetosphere:
  - reconnection process: drivers and consequences
  - plasma transport (convection, turbulence, drifts)
  - particle acceleration at reconnection fronts
• Radiation belt dynamics:
  - injections, wave growth & propagation, particle diffusion
• Magnetosphere-ionosphere coupling:
  - Field-aligned currents, the aurora and conductivity effects
• Lunar exosphere and its plasma environment:
  - Reflected particles, current-driven instabilities
• Projects: THEMIS, ARTEMIS, ELFIN
“Homegrown” experiments

THEMIS (2007)

ARTEMIS (2011)

ELFIN in vibration testing at NASA/Wallops

ELFIN (2017)
Magnetic reconnection: energy storage and release in the magnetosphere
THEMIS has established that reconnection fronts “drive” bursty bulk flows, transport most of the flux earthward and link nightside Rx to the inner magnetosphere.

The optical signature of this linkage are the streamers, emanating from polar boundary intensifications, propagating towards and activating the pre-existing quiet time arc.
An unprecedented view afforded by a “Heliophysics System Observatory”

The fronts accelerate and heat ions and electrons bringing fresh, anisotropic populations to the inner magnetosphere

Angelopoulos et al., Science, 2013
How much energy is processed during this (fairly typical) substorm?

\[ W_L^{\text{init}} = \int \frac{B^2}{2\mu_0} \, d^3V \sim \frac{B^2 A^2 L}{2\mu_0 A} \sim \frac{\Phi_{\text{init}}^2 L}{2\mu_0 A_{\text{init}}} \sim \frac{(1.2GWb)^2 60R_E}{2\mu_0 (4\pi 38^2 R_E^2)} \sim 4.8 \times 10^{15} \, J = 4.8 \, PJ \]

\[ W_L^{\text{init}} - W_L^{\text{fin}} = 4.8 - 1.9 \, PJ \sim 2.9 \, PJ \]

E.g. 7.1 magnitude quake = 2.8PJ

“Ivy King”: most powerful pure fission bomb = 2.1PJ
Where does energy conversion take place? At the reconnection fronts: Most is not in $J_yE_y^{\text{MHD}}$! (but due to electron non-gyrotropy and inertia).

Local flux transport at THEMIS (P3) and ARTEMIS (P2)

$J_yE_y$ is $2-5 \times J_yE_y^{\text{MHD}}$

Reconnection front $(B_z>0)$

Reconnection front $(B_z<0)$

Energy conversion

$P3: 50\text{GW}/R_E^2$

$P2: 5\text{GW}/R_E^2$

$20\text{km}$

$150\text{km}$
Numerical Simulation Studies of Magnetotail Reconnection
M. Ashour-Abdalla, R. Walker

Multiscale approach:
- Combine global MHD with implicit PIC model (iPic3D) using a large-scale simulation system (30 $R_E \times 12 R_E \times 12 R_E$).

Method:
- Run MHD simulation with upstream solar wind parameters.
- At onset of tail reconnection place 3D iPic3D box ($-45 < x < -15$, $-3 < y < 9$, $-9 < z < 3$).
  \[ \Delta_{\text{PIC}}/d_i = 0.06 \quad \Delta_{\text{PIC}}/d_e = 1.0 \quad m_i/m_e = 256 \]
- Use initial and boundary conditions from iPic3D code taken from MHD simulation:
  \[
  n_e = n_i = n_{\text{MHD}}, \quad v_e = v_{\text{MHD}} + m_i J_{\text{MHD}}/q_e, \\
  T_i = 5T_e = T_{\text{MHD}}, \quad v_i = v_{\text{MHD}} + m_e J_{\text{MHD}}/q_i.
  \]
- Inject particles with a drifting Maxwellian based on MHD values. Run simulation for 153s.
Time Development of $V_{\text{ex}}$ and $V_{\text{ix}}$ on the Maximum Pressure Surface

$V_{\text{ex}}$ (km/s)  $T = 115$ s  $V_{\text{ix}}$ (km/s)

$T = 153$ s

UCLA 09/22/2015
Comparative View of Measures of the Electron Diffusion Region

- Perpendicular Slippage
- Ohm’s Law
- Agyrotropy

UCLA 09/22/2015
Magnetospheric Multi Scale (MMS)
C.Russell, R. Strangeway

- Magnetospheric Multiscale (MMS) is a four-spacecraft mission to investigate magnetic reconnection.
  Mission has two phases – Phase 1: Dayside; Phase 2: Nightside
- Main payload – Solving Magnetospheric Acceleration, Reconnection and Turbulence (SMART), PI J. Burch (SwRI)
- The FIELDS instrument (PI R. Torbert, UNH) is part of the SMART payload. FIELDS includes fluxgate (DC) magnetometers with C. Russell, UCLA, PI
- Science team at UCLA includes: Robert Strangeway (Research Scientist) Cong Zhao (Grad. St.)
Example to the right shows multiple magnetopause crossings

Data were acquired on August 28, 2015 – plot shows ~ 1 minute of data

The MMS spacecraft were in a tetrahedron configuration ~ 160 km separation

Even on this scale the spacecraft saw significantly different signatures

Primary mission objective is capture magnetic nulls and resolve structure on ion versus electron spatial scales

Understanding the role of turbulence is also an important mission objective

The SMART instrument suite has unprecedented temporal resolution for in situ space-based particles and fields measurements

MMS has an open data policy – in the Spring of 2016 science-grade data will be made available to the public within one month of acquisition
Through planning of the THEMIS orbits a number of experiments have been designed in the next 2 years to study reconnection, its drivers and its effects in conjunction with the recently launched MMS mission.

THM and MMS study dayside and nightside reconnection simultaneously; VAP determines geoeffectiveness of reconnection flows; ARTEMIS measures global energy conversion.
Saturn’s magnetospheric periodicities
M. Kivelson

- Radio-frequency power (SKR) emitted
  From Saturn’s low altitude magnetosphere is modulated at \(\sim\)Saturn’s rotation period.
- The magnetosphere changes size and shape at the same period.
- But Saturn’s magnetic field is axially symmetric; how is periodicity imposed?
- Measurements show that the periodic variations arise from current flowing at high equatorial altitude.
- Source of modulation not understood.
  Electric currents must couple the N and S ionospheres to each other & to magnetosphere. May relate to angular momentum transfer to solar wind.
To determine the structure and dynamics of the Sun’s coronal magnetic field, understand how the solar corona and wind are heated and accelerated, and determine what mechanisms accelerate and transport energetic particles.

Observations inside 20Rs:

- Coronal magnetic structure still channels the flow
  - Waves, turbulence are strongest
- Temperature maximum.
- Collisional - Collisionless transition.
Venus Flyby #1
Sept 28, 2018
Venus Flyby #2
Dec 22, 2019
Venus Flyby #3
Jul 6, 2020
Venus Flyby #4
Feb 16, 2021
Venus Flyby #5
Oct 11, 2021
Venus Flyby #6
Aug 16, 2023
Venus Flyby #7
Nov 2, 2024
Launch
July 31, 2018
First Perihelion
at 35.7 \( R_S \)
Nov 1, 2018
First Min Perihelion
at 9.86 \( R_S \)
Dec 19, 2024
Joint SPP – SO observations

SO & SPP observe the same energetic particles along a magnetic field line. SO observes the acceleration site remotely.

Coronal plasma
~10 hours of transit time at ~150 km/s

SO observes remotely the plasma low in the corona (UV spectra) and at 9.5 $R_S$ (SoloHI); SPP measures plasma in situ at 9.5 $R_S$ and with SPP/Hi out to >50 $R_S$. 

SO/SPP

SPP/SO

SPP/SO

SPP@9.5 $R_S$
SO@50 $R_S$
Trace the flow of energy that heats the solar corona and accelerates the solar wind

\[
\frac{\partial z^\pm}{\partial t} + [(U \pm V_a) \cdot \nabla] z^\pm + (z^\mp \cdot \nabla)(U \mp V_a) + \frac{1}{2}(z^- - z^+) [\nabla \cdot V_a + \frac{1}{2}(\nabla \cdot U)] =
\]

\[-(z^\mp \cdot \nabla) z^\pm - \frac{1}{\rho} \nabla p_{tot}\]

\[z^- \ll z^+ \quad \delta \rho / \rho \ll 1 \quad \delta |B| \ll b |\]
Mauve: Max/Min complexity curves. Black: Fractal Brownian motion. Red: Helios at 0.4 AU @ 6 sec res. IMF total. Blue: Helios at 0.95 AU @ 6 sec res. IMF total. Red curve is quadratic fit. Helios at 0.4 AU has on ave. higher complexity than Helios at 0.95 AU.

Is this evolution of chaos/turbulence with increasing distance from the Sun?
Exciting Space Plasma Posters!

- Vassilis Angelopoulos: “Electromagnetic energy conversion at reconnection fronts”
- Xiaojia Zhang: “Predominance of ECH wave contribution to diffuse aurora in Earth's outer magnetosphere” ——> ECH?
- Jiang Liu: “Plasma acceleration in the inner magnetosphere from localized dipolaring flux bundles.”
- Yukinaga Miyashita: “Development of the near-Earth magnetotail and the auroral arc associated with substorm onset: Evidence for a new model”
- Anna Tenerani: “Trigger of Fast Reconnection via Current Sheet Collapse”
- Fulvia Pucci: “Fast Magnetic Reconnection: the Hall effect”
- Ray Walker: “Numerical Simulation Studies of Magnetotail Reconnection”