In–Situ vs. Remote Sensing

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Fundamental Science Questions

• How does the magnetosphere respond to variations in the solar wind and the IMF?
• What kinetic processes are responsible for magnetic reconnection at the magnetopause and in the tail?
• How are energy-transfer processes coupled from the microscale to the mesoscale to drive magnetospheric dynamics?
• How is solar–wind energy coupled into and through the magnetosphere and eventually deposited as energetic particles in the aurora and radiation belts?
• What is the role of ionospheric plasma in the solar–wind magnetosphere interaction?
• How are charged particles accelerated impulsively to very high energies during substorms?
Challenges to In–Situ Measurements and New Developments with MMS

• In–situ measurements are crucial for investigating physical processes at the microscale and their coupling to the mesoscale. Macroscale magnetospheric “imaging” can also be performed with large constellations of in–situ spacecraft.

• To be useful, the measurements must be made over the full relevant range either in velocity space or in the frequency domain and with the necessary time resolution and sensitivity.

• The greatest needed improvement is in the area of time resolution of plasma measurements because these have historically been tied to spacecraft spin rates. For MMS a factor of 100 improvement was needed and achieved with multiple sensors with electrostatically scanned fields of view.

• Another major issue has been the inability to measure minor species such as O⁺, He++ and He+ in the keV range near the magnetopause where solar wind protons have very high fluxes. For MMS this problem has been solved with a technique to reduce the proton flux by a controlled amount by up to a factor of 1000.
Important Scale Sizes

- Unstable, thin current sheets have thickness $< 1000$ km
- “Electron diffusion region” thickness is of order 10 km
- Current sheet motion is typically 10 to 100 km/s
- Required resolution for electron diffusion region is $\sim 30$ ms
MMS Fast Plasma Investigation

Objective:
Image full sky at 32 energies: electrons in 30 ms, ions in 150 ms

Design Concept:
Four ion and four electron dual deflecting-aperture top hat sensors for field of view and aperture

Specifications:
Electrons: 1 eV to 30 keV resolving 17% at 30 ms cadence
Ions: 1 eV to 30 keV resolving 8% at 150 ms cadence
   Angular: resolve 11 deg
   Provide 8 ea 180 x 11 deg aperture fans
   Electrostatic deflection: ± 22.5° for each aperture fan
Magnetospheric Ion Flux Ranges
The Hot Plasma Composition Analyzer on MMS utilizes a two-stage top-hat analyzer to increase the dynamic range of ion composition measurements.

- In the first stage (yellow) the ions are pre-filtered into a selected energy range.
- In the second stage (blue) the protons are reduced by a controlled amount with an RF electric field that is superimposed on the DC deflection field.
- In this second stage, the protons execute large-amplitude oscillations and collide with the analyzer walls while the heavy ions execute small-amplitude oscillations and are transmitted through the analyzer.
Performance of MMS HPCA

• With the RF field applied the proton flux is reduced by a controlled amount up to $10^{-3}$, while He$^+$ and O$^+$ fluxes are largely unaffected.

• This technique uses adjustable frequencies in the 5 MHz range and amplitudes in the range of a few hundred volts.
The Use of Large Arrays of Spacecraft

- Large arrays or constellations of spacecraft can be used to investigate magnetospheric dynamics at the macroscale.

- Because of resource limitations, as the number of spacecraft increases the number of measurements must decrease.

- At a minimum such constellations need to measure magnetic fields and plasma moments for comparison and verification of MHD models.
Magnetospheric Constellation

- Large-scale arrays of multiple spacecraft can be used to verify dynamic MHD models of the magnetosphere and trace plasma transport and energization throughout the magnetosphere.
- MC would deploy a constellation of small spacecraft each with resources of 20–25 kg and 15–18 W.
- 30+ MC spacecraft placed in elliptical (1 x 27 R_E) equatorial orbits with mean separation of ~2 R_E.
- Payloads might include magnetometers, 3D plasma and 2D energetic particles.
Challenges to Remote-Sensing Measurements:

• Remote-sensing measurements are crucial for investigating large-scale dynamics of the magnetosphere and for setting the context for in-situ measurements.

• To be most useful, images must be made continuously at relevant time scales, and ENA images need to be deconvolved into ion images.

• The greatest needed improvement is to extend imaging from the inner magnetosphere to the magnetospheric boundary regions.

• The most pressing current need is for continuous real-time imaging of both electron and proton auroras.
Energetic Neutral Atom Imaging

• Ring current imaging at two-minute cadence from IMAGE–HENA.
• This type of imaging provides a global view sorted by energy and mass species for E/q in the keV to 100s of keV range.
• Images depend strongly on viewing direction because of the optically-thin medium, and this can be improved with stereo imaging as on TWINS.
Post-Midnight Ring Current Injection

• Images like this one show that the ring current is injected near or after midnight (rotating toward dawn for high positive IMF $B_y$) rather than in the dusk–midnight hemisphere as previously thought.
• This result is consistent with the main-phase magnetic-field perturbation being due to field-aligned currents as suggested by Harel et al. [1981].
Equatorial ENA Images of the Ring Current

- Ring current imaging from an equatorial perspective with IMAGE-HENA.

- This type of imaging provides field-aligned distributions sorted by energy and mass species for E/q in the keV to 100s of keV range.
EUV Imaging of the Plasmasphere

• Resonantly scattered sunlight allows imaging of He⁺ for densities above about 40/cc.
• As shown, these images can reveal the global position of the plasmapause and plasma tails as well as the helium airglow and the EUV aurora.
• On IMAGE the EUV camera provided global images on a 10 minute time scale, which is sufficient for plasmasphere studies.
• The plasmaspheric tails eventually intersect the magnetopause, so a combination of plasmaspheric imaging and magnetopause imaging would be a powerful tool.
The Evolution of Plasmaspheric Structures

• In addition to plasma tails, several other structures such as the shoulders in the dawn sector shown here, were discovered by IMAGE.

• The shoulders were found to result from northward IMF transitions, which caused impulsive decreases in the convection electric field.

• As shown here the plasmaspheric images depend sensitively on the orbital position of the observing spacecraft.
Proton Aurora Imaging

• Global imaging of precipitating protons was first performed by the IMAGE FUV instrument.

• Among the discoveries resulting from proton aurora imaging were (1) detached arcs in the afternoon sector, which result from S–N and W–E rotations of the IMF and (2) proton auroral spots formed in the cusp ionosphere by precipitating protons originating in northward–IMF reconnection regions.
Cusp Auroral Spot

- (Top) Cluster observes reconnection jets at the magnetopause [Phan et al., 2003].
- (Bottom) Continuous reconnection for northward IMF is shown by the series of IMAGE proton aurora images during a 3.5-hr. interval with positive $B_z$ and high solar wind dynamic pressure (~17 nPa).
- The proton spot shifts in MLT in response to $B_Y$ [Frey et al., 2003].
X-ray Emissions from Comets

- X-ray emissions were unexpectedly observed from comets by ROSAT.
- These were explained by Cravens [1997] as being caused by charge exchange of high charge–state solar–wind ions (e. g., $O^{7+}$ and $O^{8+}$) into excited states, which emit X-rays when they decay to the ground state.
- This result then provided an explanation for high background observed by ROSAT and other X-Ray astronomy missions resulting from charge exchange of high charge–state solar–wind ions in the Earth’s extended exosphere.

Lisse et al. [1996]
X–Rays Produced by Solar Wind Charge Exchange at Earth

Cravens et al. [2001]
Simulations of Magnetospheric X-Ray Imaging

Bow Shock and Cusp

Courtesy of M. Collier, GSFC
Simulations of Magnetospheric X–Ray Imaging

Foreshock and Magnetosheath

X-ray intensity is a function of both the plasma density and the exospheric H density.

Courtesy of M. Collier, GSFC
Combined Imaging and In-Situ Measurements

- A proposal for a constellation of spacecraft that can image the magnetosphere in electron density while simultaneously making distributed in-situ measurements was advanced by Ergun et al. [1998].

- This idea (tomographic imaging) uses radio waves transmitted between multiple spacecraft to obtain total column density. By combining many columns, a 3D tomographic image can be obtained.

- A simulation is shown on the next slide.
Magnetospheric Tomographic Imaging

• The phase velocity of EM waves in a plasma depends on the wave frequency and the plasma density.

• By transmitting two phase-coherent signals with different frequencies (e.g., 1 and 3 MHz) between two s/c the resulting phase shift between the two signals will provide the line-of-sight integrated electron density.

• A multi-spacecraft constellation (e.g., 16 s/c) can provide global maps of electron density using tomography based on many line-of-sight densities.

• The s/c should also carry plasma and field instrumentation to allow both physics and context to be revealed.
Summary

- The large-scale dynamic configuration of the magnetosphere and the circulation and acceleration of plasma within it in response to solar-wind variations have been studied with many s/c over the last 50 years.
- However, major outstanding questions still exist, primarily because of (1) rapid time variations and boundary motions in the crucial energy-transfer regions and (2) the lack of simultaneous measurements at the micro, meso, and macro scales.
- Careful coordination of remote-sensing and in-situ measurements can lead to closure on many questions.
- Examples of the power of coordinated measurements include the mapping of an X-line (Cluster) to a cusp auroral spot (IMAGE) and the simultaneous imaging and in-situ probing of