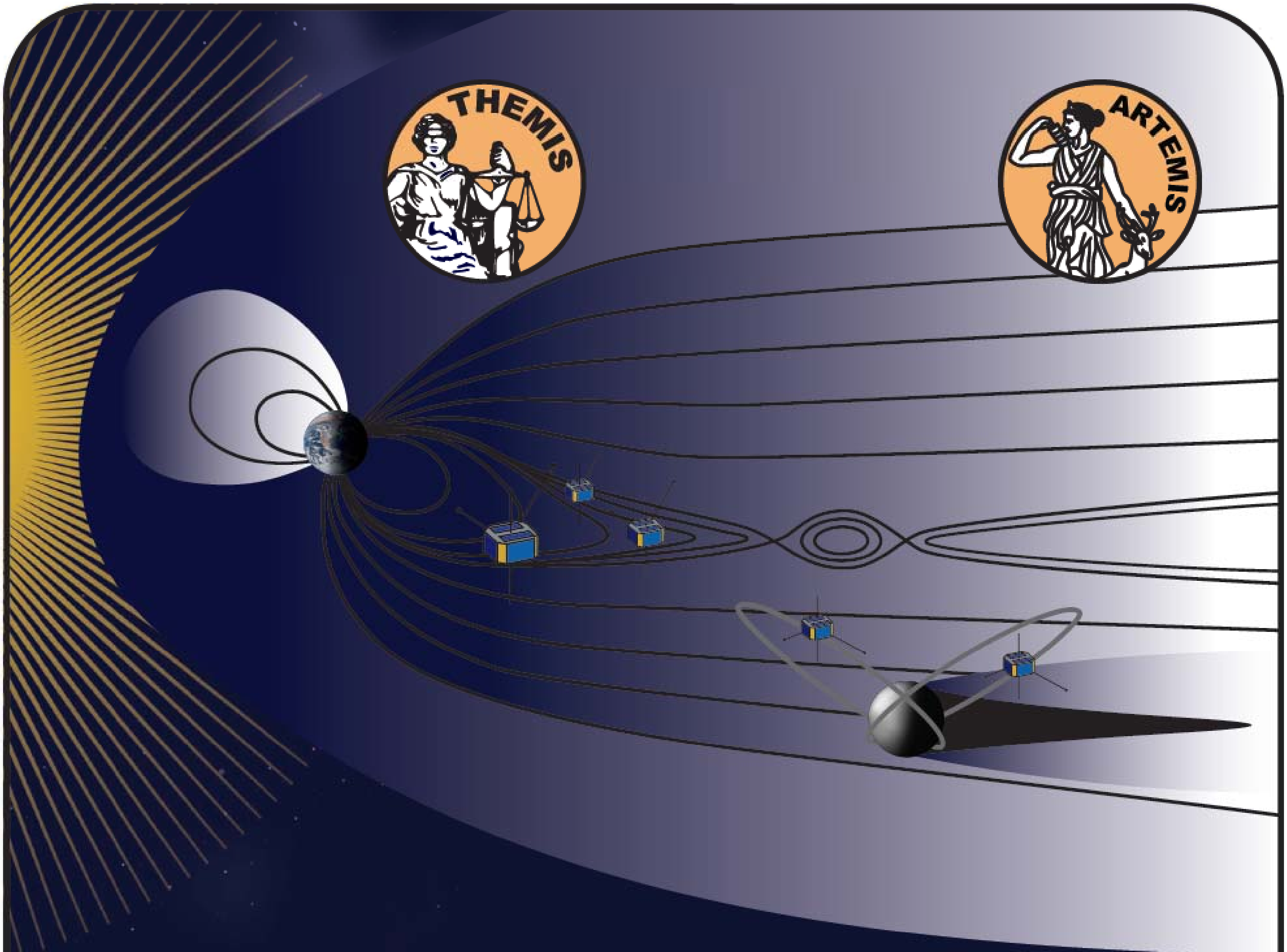

Time History of Events and Macroscale Interactions during Substorms: THEMIS

AND

Acceleration, Reconnection Turbulence, and Electrodynamics of Moon's Interaction with the Sun: ARTEMIS

PROPOSAL SUBMITTED FOR:

SENIOR REVIEW 2008 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM

FOR THE

HELIOPHYSICS OPERATING MISSIONS

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Ready Reference Sheet

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Table 0A: THEMIS Facts:

Launch	**February 17, 2007, Cape Canaveral**
Current Orbits	**P1, 1.2 x 31.7 R_E, i = 3.2°, T = 94.0 hours** **P2, 1.3 x 19.6 R_E, i = 6.7°, T = 47.5 hours** **P3, 1.4 x 11.8 R_E, i = 6.5°, T = 23.9 hours** **P4, 1.4 x 11.8 R_E, i = 7.1°, T = 23.9 hours** **P5, 1.5 x 9.9 R_E, i = 11.5°, T = 19.2 hours**
Spacecraft (5)	**All subsystems healthy**
Instruments (5/spacecraft)	**Electrostatic analyzers (ESA): All healthy** **Solid state telescopes (SST): All healthy** **Search coil magnetometers (SCM): All healthy** **Fluxgate magnetometer (FGM): All healthy** **Electric field instrument (EFI): All healthy**
Ground based observatories (GBO)	**All-sky white light imagers (ASI): All healthy** **Fluxgate magnetometers (GMAGS): All healthy**
E/PO observatories	**12 schools with E/PO magnetometers: All healthy**
End of baseline mission	**September 2009**

Table 0B. Mapping Review Criteria to Proposal Sections

Criterion	**Section**	**Comment**
Relevance to HP research objectives	2. Introduction	Multiple HP objectives, Table 2B
Participation in Heliophysics Great Observatory	2. Introduction	Plays well with others
Promise of future impact	3. Extended Baseline Mission 4. ARTEMIS 6. Results to date	New orbits, New science objectives, Active team
Budget/cost efficiency	7. Technical Budget	Initiate GI program ARTEMIS cheaper than new mission Effective use of dying probes Effective management/ops
Technical status/Probe and instrument health	7. Technical/Budget	100% healthy
E/PO activities	9. Education/outreach	School magnetometer network, lesson plans
Broad accessibility and usability of data	8. External use of data Appendix: MAP	All data/tools online. Archive backed-up
Results evidenced by citations, press releases	8. Public Affairs	Media coverage /Fall AGU
Productivity: Publications and young scientists	7. Discoveries 8. Public Affairs	>40 talks, Fall AGU; 30 GRL papers submitted
Mission Archive Plan	Mission Data Archive Plan	Cooperation with SPDF

1. Executive Summary

THEMIS a five satellite (a.k.a probe) constellation mission, was launched on February 17, 2007 (Angelopoulos, TSRR). After a successful instrument commissioning & inter-calibration, "coast phase" science at the dayside magnetopause, and positioning of the five probes in their final science orbits on December 4th 2007, THEMIS is returning intriguing, groundbreaking data from its first prime (tail) season.

The health of the constellation is excellent, as demonstrated by numerous discoveries from the coast phase (see Section 6), and 30 publications submitted to the special THEMIS issue of Geophysical Research Letters. Of those, 25% are by scientists not affiliated directly with the co-I team or funded by THEMIS, and more than 40% are by young researchers. Discoveries, including the source of a substorm's surge in the magnetotail; a detached flux transfer event; and the first observations of the birth of a hot flow anomaly in the solar wind, herald the mission's tremendous potential. They have been well covered by the press and electronic media, including CNN's most popular science stories. Highest quality data, analysis code, and documentation are routinely available on the main web page (http://themis.ssl.berkeley.edu/) and are also served via an increasing number of mirror sites (France, Japan, Canada). THEMIS supports users by its "THEMIS_Science_Support@ssl.berkeley.edu" help line and updates users through its "THEMIS-science-support-announce" mailing list. Well-attended software demos are conducted at major meetings. With hundreds of hours of substorm observations under its belt, and more than a handful of "classic" reconnection and current disruption events already acquired in tandem, THEMIS will easily satisfy its prime objectives by September 2009.

Once the prime mission goals are met, the THEMIS team proposes to use the three inner probes on an extended mission of new discoveries. The probes will be placed in clustered (tail/dayside) or "string-of-pearls" (dawn-dusk) orbits at progressively smaller scales never before attained in the equatorial near-Earth magnetosphere inside of $12R_E$. From $2R_E$ down to ion gyroradii (~100km) separations probes P3,4 & 5 will address fundamental processes: the structure of the near-Earth current sheet, the role of waves and large electric fields in inner magnetosphere and the physics of asymmetric reconnection and particle energization at the sub-solar magnetopause. THEMIS will answer pressing Heliophysics questions, which are also timely given the impending launch of RBSP in 2012 and MMS in 2014.

To optimize the science yield of its outermost two probes and to evade detrimental long shadows in March of 2010, we propose to send P1 & P2 into stable, lunar equatorial orbits, where they will form the new mission ARTEMIS. From 100s of km to $20R_E$ separations at lunar distances, probes P1 and P2 will make the first systematic, two-point observations of distant magnetotail phenomena with comprehensive instrumentation. ARTEMIS will resolve outstanding questions regarding particle acceleration, reconnection and turbulence in the magnetotail and the solar wind, and study the formation and dynamics of the lunar wake from 1500km–$30R_L$.

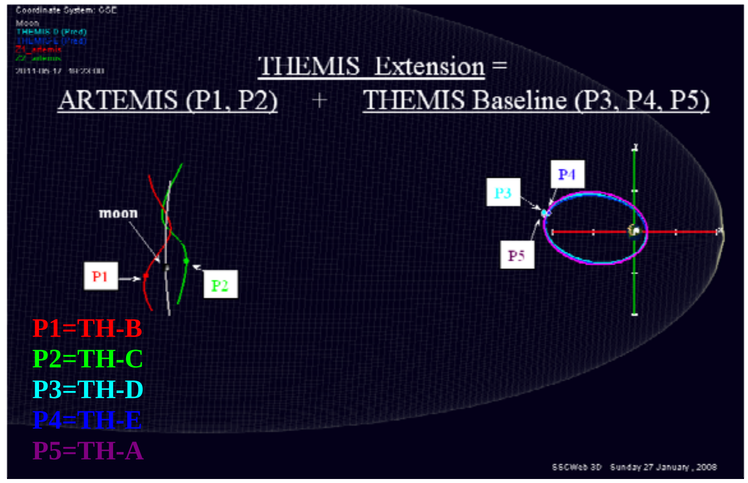

Figure 1A. THEMIS extended baseline and ARTEMIS. Insert shows probe number assignments to probe letters, which was done after early checkout. The orbits are publicly available for plotting at: http://sscweb.gsfc.nasa.gov/tipsod For THEMIS P3, P4 and P5 select THEMIS_D,E,A (pred); for ARTEMIS: Z1,2_artemis; for the moon click on: "Moon".

THEMIS and ARTEMIS complement other Heliophysics missions. Working with FAST overpasses of its ionospheric footprints and Cluster and Geotail traversals further out in the tail or solar wind, they enable a comprehensive exploration of the Sun-Earth system. With flexible architectures, a single management team, readily available data products and unified analysis tools they perform ground-breaking science at a far lower cost than a dedicated mission to lunar orbit and represent the most efficient utilization of Heliophysics resources to answer the discipline's outstanding questions in the regions they visit. They are in line with the Heliophysics goals and objectives as demonstrated in Table 2A. In addition, ARTEMIS is aligned with the NAC/NRC recommendations to characterize the lunar environment and predict space weather impacts on robotic and human productivity. It also supports the Vision for Space Exploration by being the first mission to use prolonged residence in Lunar Libration Orbits. *By funding THEMIS and ARTEMIS, NASA expands its frontiers of knowledge in science and technology with novelty and efficiency. Together the two missions can form the anchor of NASA's Heliophysics Great Observatory in the magnetosphere and at the moon for years to come.*

Table 1A: Prime (FY08-09) and Extended (FY10-12) THEMIS Science Versus Mission Phase

Phase	Abbr	Time Interval	Prime mission: P1, P2, P3, P4, P5	Objective
Coast	**Coast**	Jul. 07-Oct. 07	5-probes "string-of-pearls", APG=14.7R_E	Commissioning & Calibration Bonus: Boundary waves/FTEs
First Tail	**T1**	Dec. 07-Apr. 08	APG=10,12,12,19.5,31 R_E, once/4days	Substorm onset
First Dayside	**D1**	Jul. 08-Oct. 08	APG=11,12,12,19.3,30.7 R_E, once/8days	SW coupling, subsolar mpause
Second Tail	**T2**	Jan. 09-Mar. 09	APG=12, 12, 12, 19, 31 R_E align once / 4 days	Substorm onset, Macroscale interactions
Second Dayside	**D2**	Jul. 09-Oct. 09	APG=12.9, 11.6, 11.6, 19.5, 30.4 R_E align every 8 days	SW coupling, flanks
Whole Mission	**R**	Throughout mission	Two passes per day / probe through radiation belts	Sources/sinks of particle populations, track injections
Phase	**Abbr**	**Time Interval**	**Extended Baseline THEMIS: probes P3, P4, P5. T~24hrs, r_A=12 R_E**	**Objective**
3rd Tail	**T3**	Mar. 10-May 10	dZ=600-3000km, dR = 1R_E, once/8days	Thin current sheets, turbulence
3rd Dayside	**D3**	Sep. 10-Nov. 10	dZ=1000-3000km, dR=1000km, daily	Rx, cold plasma quenching
4th Tail	**T4**	Apr. 11-Jun. 11	dZ=100-500 km, dR=1000 km, daily	Thin current sheets, turbulence
4th Dayside	**D4**	Oct. 11-Feb. 12	dZ = 200-1000 km, dR = 200 km, daily	Kinetic scale reconnection
5th Tail	**T5**	May 12-Aug. 12	dZ = 100-500 km, dR = 1000 km, daily	Thin current sheets, turbulence
Dawn & Dusk	**IM4, IM5**	Between Tail and Dayside Phases	3-probes "string-of-pearls": ~100 km – 1 R_E separations along-track	Strong E- field, wave effects on particle source/losses
Phase	**Abbr**	**Time Interval**	**Extended ARTEMIS: probes P1, P2.**	**Objective**
Translunar Injection	**TLI**	Oct. 09-Oct. 10	Translunar orbits to capture into LL1,LL2	Mission Operations only
P1 at LL2, P2 at LL1	**LL1,2**	Oct. 10-Jan. 11	$d\mathbf{R}_{P1-P2}$=20R_E at moon, i.e., 60± 4R_E $d\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth dX^{GSE}_{P1-P2} ~ dY^{GSE}_{P1-P2} ~ 500km-20R_E	*In the Magnetotail:* Rx, SW-magnetosphere interaction, tail turbulence
P1,P2 at Lunar Libration 1	**LL1**	Jan. 11-Apr. 11	$d\mathbf{R}_{P1-P2}$=5-20R_E at moon: (60± 4R_E) $d\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth dX^{GSE}_{P1-P2} ~ dY^{GSE}_{P1-P2} ~ 500km-20R_E	*In the Solar Wind (SW):* Foreshock, shock acceleration, Rx, SW turbulence
Lunar orbit	**LO**	Apr.11-Sep.12	$d\mathbf{R}_{P1-P2}$=500km-5R_E at moon: (60±4R_E) $d\mathbf{R}_{P1-P2}$ along/across Wake & Sun-Earth	*In the Wake (SW or Tail)* Kinetics and dynamics of lunar wake in SW, sheath, tail
Phase	**Abbr**	**Interval**	**THEMIS and ARTEMIS in Tandem**	**Objective**
n/a	**n/a**	T3, T4, T5 (above)	Near- and mid-tail simultaneously	Birth and Retreat of Plasmoids Dissipation of Rx flows

Key: T=Tail; D=Dayside; IM=Inner Magnetosphere; Rx= Reconnection; APG=apogee; R_E =Earth radii

2. Introduction: The Prime Mission (FY08/09) and Future Plans (FY10-12).

During the 6 months following launch on February 17, 2007, the five THEMIS probes operated in a 'string-of-pearls' configuration with an apogee of 14.7 R_E. Using observations from this array and the dedicated network of 20 ground observatories in North America, members of the THEMIS team: (1) validated the combined space- and ground-based substorm onset timing techniques that underpin the mission concept, (2) studied the structure of the magnetopause, magnetosheath, bow shock, and foreshock, and (3) began to survey the unusually quiet inner magnetosphere during solar minimum. Forty papers from this 'coast' phase of instrument commissioning were presented at the Fall 2007 AGU and additional papers were presented at topical meetings in the US and Europe. More than 30 papers have been submitted to a special issue of GRL, and many others are being submitted to special THEMIS issues of SSR and JGR. All known THEMIS publications can be found at: http://themis.ssl.berkeley.edu/publications.shtml.

From September to December 2007, the THEMIS probes moved into their individual orbits in preparation for their primary science objectives and first season of magnetotail observations. Because the differing probe apogees align radially once every four days over North America, the constellation of spacecraft (henceforth called "probes") and ground arrays can be used to pinpoint when and where the onset and expansion phases of a substorm begin - crucial information needed to discriminate between proposed causes in terms of current disruption, magnetic reconnection, and other mechanisms.

At onset, the most equatorward auroral arc brightens and moves poleward. As illustrated in Figure 2Aa, the near-Earth (or current disruption, CD) model predicts that disruption of the near-Earth current sheet by an as yet unknown plasma instability causes the brightening, while a tailward-propagating rarefaction wave triggers reconnection in the mid-tail at distances some 20 to 30 R_E from Earth. The disruption causes the near-Earth magnetic field to dipolarize and diverts currents into the ionosphere, while the fast mode wave initiates sunward-moving fast flows. Both activities contribute to poleward arc motion. By contrast, the mid-tail model evokes reconnection (Fig. 2Ab), which launches earthward- (and tailward-) moving flow bursts at speeds of several hundred km/s. The flow bursts brake when they encounter the strong magnetic fields within the inner magnetosphere, resulting in flux pile-up and a dipolarization of the magnetic field. A substorm current wedge forms where cross-tail (dawn-to-dusk) currents are diverted into the ionosphere by the inertial currents and by the sustained build up of a north-south gradient of plasma pressure. As more flow arrives, the magnetic field dipolarization front propagates tailward, resulting in the poleward arc motion.

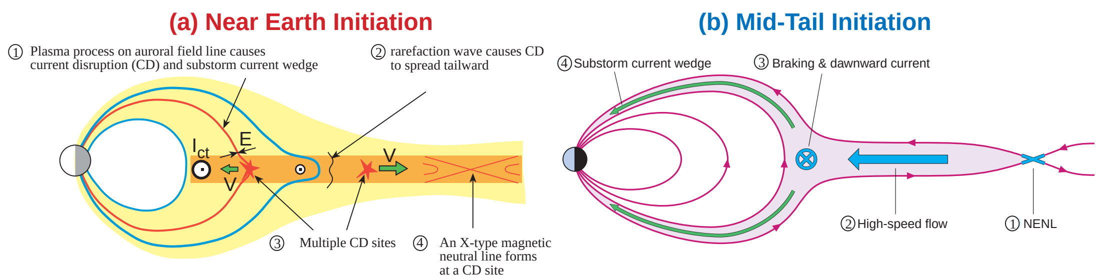

Figure 2A: Two models for substorms illustrate the time sequences to be tested by THEMIS.

Two seasons (January to March of 2008 and 2009, see Table 1A) will provide tens of substorms with the inner probes separated first in the X-Y and then in the Y-Z planes. Due to the seasonal distortion of the plasma sheet relative to the orbital configuration, the optimal constellation conjunctions (outer probes within ±5 R_E of the neutral sheet at pre-midnight), start around Feb. 21, 2008. On the basis of preliminary studies like that described in Figure 2B, we expect to resolve: (1) where the global substorm instability is triggered in the tail, (2) the causal link between current disruption (CD) and near-Earth Reconnection (Rx), (3) the generation and coupling of field-aligned currents and (4) the cross-scale coupling between large azimuthal wavelength (field line resonances and Kelvin-Helmholtz waves) to localized instabilities (shear-Alfven & kinetic Alfvén modes). These Level 1 objectives mandate 1-20 R_E inter-probe separations throughout the prime mission.

These same orbits will also prove invaluable in addressing longstanding questions regarding geomagnetic storms and the dayside solar wind-magnetosphere interaction. By the end of the prime mission in September 2009, the probes will complete an extensive survey of the inner magnetosphere. By measuring the radial profile of the electron phase space density at time-scales of 2-4hrs (separations of 5-10 R_E) commensurate with the time/spatial scales of electron transport, THEMIS will determine whether the source of enhanced radiation belt fluxes at storm-time recovery lies at large distances (L>10). Finally, taking advantage of the unique radial alignments during the dayside portion of the prime mission, THEMIS will track the evolution of solar wind parcels through the foreshock and magnetosheath right to the magnetopause. There, THEMIS will determine how pre-conditioning of the solar wind by the foreshock and bow-shock affects the solar wind energy coupling at the magnetopause.

Beyond September 2009, when the THEMIS probes have completed their prime mission objectives over macro-scale (1-20 R_E) separations, we will have a unique opportunity to utilize their state-of-the-art instrumentation to address critical research problems in the equatorial magnetosphere from completely new formations and over small-scale (100km – 2R_E) separations. As detailed in Section 3, our extended baseline mission employs the innermost 3 probes (P3, P4 and P5) at unique radial and Z_{gsm} separations when in the tail and dayside, and on string-of-pearls orbits at the inner magnetosphere, to address questions concerning fundamental phenomena in the near-Earth equatorial magnetosphere. Based on the excellent results obtained to date (Section 6), and our operational experience with string-of-pearls formations during the commissioning and coast phase of the mission (albeit brief), we are confident in the ability of the team to extract these results within the scope of the THEMIS 'Classic' budget (Section 7.2). Harvesting the rich discovery potential from the mission within the context of the Heliophysics Great Observatory, however, requires engaging the research community at large, via an active Guest Investigator program. We therefore request over-guide funding in THEMIS 'Low' to reinstitute a 4-year GI program, which was selected (as originally proposed) in THEMIS prime, but later rescinded by NASA HQ.

As discussed in Section 4, the outer two (P1 and P2) probes' ability to support P3, P4 and P5's science with correlative measurements diminishes beyond 2010. Additionally, the risk from prolonged (>6hr) Earth shadows increases (see Section 7.1). We thus propose to employ P1 and P2 in an entirely new mission of discovery to the Moon: ARTEMIS. Comprising the first two-probe mission around the Moon, ARTEMIS will revolutionize our picture of particle acceleration, reconnection and turbulence in the distant tail and in the solar wind, and our understanding of the formation, structure and refilling of the lunar wake. Discovery requires new scientific expertise (Table 2A) and an enhanced budget (Section 7). The ARTEMIS team, which helped optimize the science return of this mission, is comprised of the leading experts in the scientific areas addressed by this proposal and, together with the THEMIS instrument and THEMIS science operations teams, will make the scientific breakthroughs that the new ARTEMIS data enable.

Distant Magnetotail	Acceleration, Rx, Heating	Oieroset, Schriver
	Plasmoids, Tail	Slavin, Murphy
	Turbulence	Weygand, Velli
Solar Wind	Shock Acceleration	Eastwood, Bale
	Turbulence	Velli, Weygand
	Foreshock	Eastwood
Wake	Computer Sim's	Travnicek, Schriver, Farrell
	Laboratory Sim's	Gekelman
	Refilling, Beams	Halekas, Farrell, Bale

Table 2A. In conjunction with the THEMIS science team, the proposed ARTEMIS science team has the expertise and is ideally positioned to reap the full benefits of the mission's potential in the new regions it will visit.

Working in tandem, THEMIS and ARTEMIS will address the broad range of Heliophysics Roadmap questions summarized in Table 2B. Heliophysics-targeted outcomes that will be addressed by the mission include measuring magnetic reconnection at Earth, determining the dominant processes and sites of particle acceleration, identifying the key processes that couple the Sun to Earth's atmosphere, understanding how solar shocks and disturbances propagate to Earth (foreshock and shock/magnetosphere interaction), identifying how space weather (radiation belt) effects are produced in near-Earth space, determining extremes of the variable radiation and space environments at Earth and the Moon, and now-casting solar and space weather (predictability of substorms and storms). Sections 3 and 4 provide further details.

Achieving the objectives of the extended phase requires THEMIS/ARTEMIS to engage the full national/international research community. The THEMIS team already relies upon solar wind observations by ACE and Wind, auroral observations by POLAR and FAST, magnetospheric observations by Geotail and Cluster and provides information concerning magnetospheric conditions to FAST, TIMED, and SAMPEX. Recognizing our responsibility to enable these collaborative projects to reach their full scientific potential, we have placed our dataset, documentation, and analysis software on-line for downloading, and conducted, in conjunction with various scientific meetings, public demos/workshops on how to use them.

THEMIS has enjoyed some notable Public Affairs and Education and Public Outreach (EPO) successes (see Sections 8 and 9). The team has worked intensely on education activities, including the operation of ground-based magnetometers at schools across the Northern United States (featured on the PBS primetime show NewsHour with Jim Lehrer, http://www.pbs.org/newshour/bb/science/jan-june07/themis_05-16.html), the development of new educational material, and the planning of future joint E/PO work with other missions. We have worked closely with the press and electronic media to promote the Heliophysics message. Our "YouTube" site, showing launch and deployment, was publicized by NASA Watch, and continues to be heavily visited.

3. Extended THEMIS Baseline Mission

Because it hosts some of the most intense space weather phenomena, the equatorial magnetosphere inside of $12R_E$ lies at the heart of magnetospheric physics. Many of the processes within this region are driven by its outer boundary, 10-12 R_E from Earth. On the nightside, relevant phenomena include particle injections during storms and substorms, intense, often highly localized, electric fields that guide the injected particles, and the processes that generate field-aligned currents and substorm aurora. On the dayside, the relevant phenomena focus on the microphysics of reconnection at the subsolar magnetopause, where most of the solar wind-magnetosphere interaction occurs.

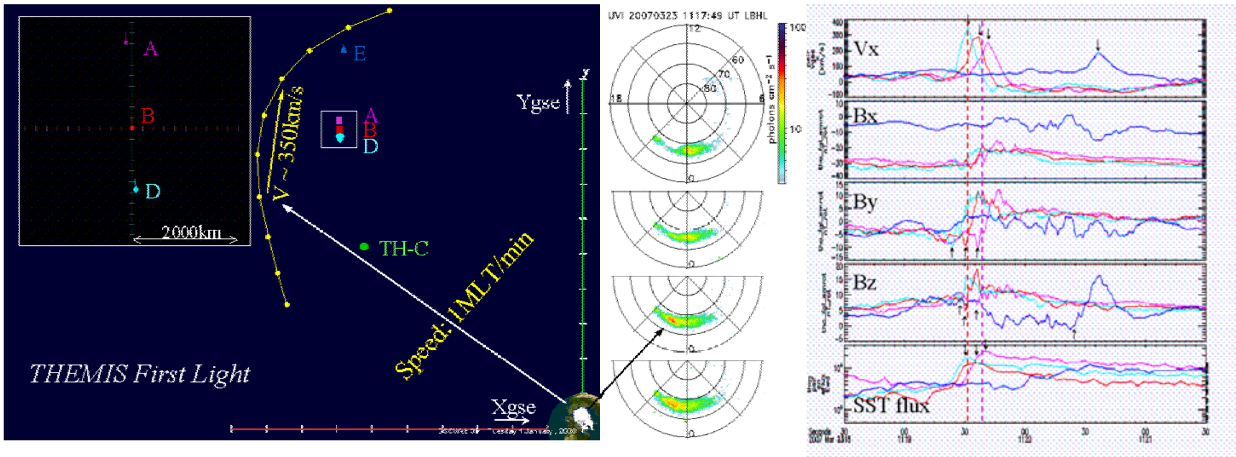

Figure 2B. First observations of a substorm onset (from Angelopoulos et al., TSSR). On March 23, 2007, the THEMIS probes were arrayed azimuthally in the pre-midnight magnetotail (left panel), where they observed magnetic field dipolarizations (Bz increase) and sunward (Vx > 0) flows associated with a substorm onset (right panel). POLAR/UVI provided images of the westward-surging substorm expansion (middle panel). The event propagated duskward from THEMIS D to E, consistent with THEMIS ground-based observations of a simultaneous auroral brightening. Assuming field-aligned currents at the edge of the expanding activation were planar, and using the measured expansion speed at THEMIS we determined that a 0.7R_E wide current sheet of ~1nA/m^2 was flowing in space. FAST, in a fortuitous overpass at the THEMIS footprint observed the expansion of the aurora, and measured the currents and their particle signatures, providing the first complete electrodynamic synthesis of a substorm current wedge. The combined set of observations serves as a proof-of-principle for the substorm studies that THEMIS (and allied missions of the Heliophysics Observatory) will conduct when THEMIS probes are in the tail.

Heliophysics Roadmap Objective		**Extended Baseline**	**ARTEMIS**
F1	Understand Magnetic Reconnection	3.1, 3.3	4.1, 4.2
F2	Understand the Processes that Accelerate and Transport Particles	3.2	4.1, 4.2
F3	Plasma-Neutral Interactions on Various Spatial Scales (Aurora/Ionosphere)	3.1, 3.2	
H1	Understand the evolution of solar activity that affects Earth (Turbulence/Shocks)		4.2
H2	Determine changes in the Earth's magnetosphere/ionosphere for specification/mitigation/prediction	3.2	4.2.4
H4	Understand role of magnetic shielding on evolution/habitability		4.2.4
J1	Characterize the variability of space environments for explorers	3.2	4.2.4
J4	Characterize space weather in planetary environments	3.2	4.2.4
NAC/NRC Report Goal: Heliophysics Science and the Moon			
1.1	Characterize lunar electromagnetic and plasma environment		4.3
1.3	Magnetotail dynamics at lunar orbit		4.3
1.4	Interaction of plasmas with the Moon		4.3
2.1	Space weather impacts on robotic and human productivity		4.3
NASA Vision For Space Exploration/Exploration Systems Architecture			
1.3	Lunar architecture uses LL1, LL2 orbits, never flown before		4.0, 7.1.7

***Table 2B:** Mapping THEMIS/ARTEMIS to the Heliophysics Roadmap, the NRC report on Lunar Science & the VSE*

THEMIS is the first multi-probe mission to visit the equatorial magnetosphere with comprehensive instrumentation. By its prime mission it will have completed two traversals (Table 1A) of this region, providing a wealth of unprecedented information at macroscale (1 to 10s of R_E) separations. The three inner probe separations during the prime tail seasons were designed to address: the question of where and when current disruption (CD) occurs, during both tail seasons; the contribution to the field-aligned current generation from the flow vorticity and the inward pressure gradient in the equatorial plasma sheet (in

T1, see Table 1A), and separately how the cross-tail current is decreased as a function of time during the current disruption process (in T2, see Table 1A). Those macroscopic prime mission questions required separations in the XY or YZ GSM dimensions in T1, and T2 respectively. Prime mission design was driven by the need to maintain large azimuthal (Y_{gsm}) separations by at least 2 probes, in order to bracket and time the CD process. YZ separations were thus not obtained. With scores of reconnection and plasmoid events identified already in the past few weeks, THEMIS is well on its way towards achieving its prime goal (e.g., see Figure 3A)

The phenomena at hand, however, couple to scales spanning from magneto-hydrodynamic (MHD) down to kinetic (100s of km). Once THEMIS answers when and where substorms begin, the THEMIS extended baseline mission will be able to address for the first time key processes in the equatorial magnetosphere, at 100s of km - $2R_E$ scales.

Specifically, probes P3, P4, and P5 at separations ranging from the thermal ion gyroradius (i.e. from 100s of km) to the local field line curvature (i.e., a few thousand km up to $1R_E$) will answer critical questions pertaining to the stability and dynamics of the near-Earth current sheet, namely the evolution of the current carriers, current diversion and filamentation, growth of critical tail instabilities at onset, and the role of turbulence on current dynamics. XZ plane separations will be used, never achieved before but ideally suited for the questions at hand. As the current density affects reconnection triggering in the presence of an otherwise stabilizing northward field, knowledge gained will prepare the field for the arrival of MMS.

During the dawn/dusk seasons of the inner magnetosphere portion of the investigation, we will bring P3, P4, P5 into a string-of-pearls formation at distances of 100s of km to $2R_E$ to determine the role of waves and strong electric fields in radiation belt and ring current dynamics. On the dayside, with inter-probe separations from an ion gyroradius up to the width of the magnetopause current layer (~200 to 1000km) we will address key questions regarding the nature of the prevailing, asymmetric reconnection and electron acceleration within it.

None of the questions above could be answered by any other mission in the past, including THEMIS-prime and Cluster (Cluster's polar orbit crosses the equator only inside of $4R_E$ and outside of $12R_E$). Analysis of these processes at separation distances of 100s-1000s of km, will permit better planning of orbits and modes for the forthcoming visit by MMS at even smaller (10's-100's km) scale lengths.

THEMIS's baseline extended mission will have the instrumentation and inter-probe separations needed to systematically fill a gap in our observations of the plasma sheet, the subsolar magnetopause, and Earth's radiation belts and ring current. The proposed extension is a natural evolution of the prime phase's macroscale separations down to the regime between an ion gyroradius and the field line curvature, where many of the key processes in the equatorial magnetosphere operate. It complements Cluster and serves as a pathfinder for MMS and RBSP.

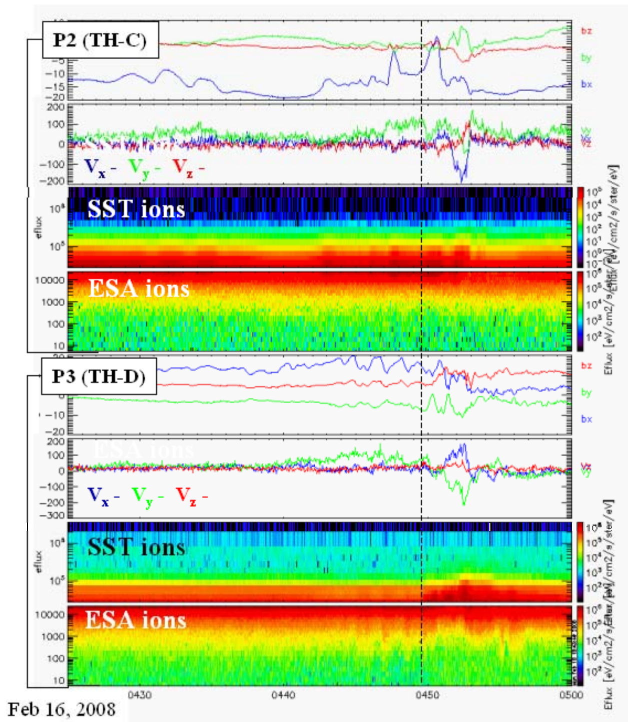

Figure 3A. Results from a THEMIS alignment during the first tail season illustrate a classic reconnection event, as well as the need for multipoint THEMIS extended baseline mission observations of the near-Earth magnetotail at active times. Magnetic fields and plasma flows at the time of a substorm onset observed by GBO station Gillam (dashed vertical line at 0451 UT). The strong antisunward flows (-Vx) observed by P2 at 18.3 R_E indicate reconnection nearer Earth. P3 and 4 separated by δY~$1R_E$, at $11R_E$ observed near-simultaneous injections (enhanced ion fluxes) and dipolarizations (Bz becomes more positive/northward). Strong Vy flows ahead of onset indicate the escape of bouncing ions from extremely curved magnetic field lines within a very thin current sheet. The leakage is interrupted during substorm onset. These unpublished results highlight the importance of understanding the current carriers, current sheet stability and current dynamics during the few minutes prior to particle injections. The extended THEMIS mission is ideally designed to tackle such questions.

3.1 Magnetotail science

The inner edge of the plasma sheet, the region between 7-12R_E, is a crucial region of the magnetosphere. It is the region where both stable and dynamic auroras map, it hosts the strongest currents supporting the magnetotail and it is where the fast flows resulting from near-Earth reconnection are expected to deposit their energy. The particle heating and electromagnetic fields generated within this region feed into the inner magnetosphere and affect ring current storm-time evolution. Therefore it is important to understand the processes in this region at all scales that are important for its dynamic evolution. The extended THEMIS baseline mission will provide new perspectives on this region, by employing sub-R_E, kinetic-scale, spacings and simultaneous radial and Z-separations to study the nature and stability of the near-Earth current sheet and the evolution and dissipation of fast, transport-efficient Earthward flows.

3.1.1 Nature of the near-Earth current sheet: The inner magnetosphere drives the field-aligned currents that are responsible for most of the energy deposited in the ionosphere. For typical current sheet thicknesses, energetic particles drifting duskward carry the cross-tail current. At dynamic times, which are the most interesting, the current sheet thins (<2000km) and energetic particles of comparable gyroradius execute Speiser orbits and leave quickly the thin current sheet. Other populations (e.g., energetic electrons) must support the current (Mitchell et al., 1990). At substorm onset and late recovery the current sheet thickens and energetic ions can again carry the current. Understanding the dominant current carriers and the plasma populations that support the structure of the tail is extremely important for understanding magnetotail dynamics and evolution.

MHD and hybrid simulations predict that the cross-tail current sheet at the inner edge of the plasma sheet bifurcates into a Y-type configuration (Figure 3B). Understanding this configuration is thought to be key to understanding current sheet destabilization during times of storms and substorms [Battacharjee et al., 1999]. Current bifurcation and filamentation down to 100s of km have been observed by Cluster beyond 15R_E, but such observations have never been made with appropriate multipoint measurements in the key transition region between tail-like and dipole-like field lines, the equatorial magnetotail at 7-12R_E. THEMIS's prime mission Z-separations in T2 are ~1R_E, and will provide only an average current density, unable to resolve the details of the current's spatial distribution.

Because the particle and magnetic field gradient scales are small, and the current sheets may be tilted away from the equatorial plane, studies of this phenomenon are only possible with simultaneous radial and vertical (Z_{gsm}) separations in the plasma sheet, on the order of 100s to 1000s of km. THEMIS's extended mission orbits and separations of 100s of km to 1R_E, will be ideal for near-Earth tail studies of current bifurcation and filamentation at active times, and for determining the importance of these phenomena for tail dynamics.

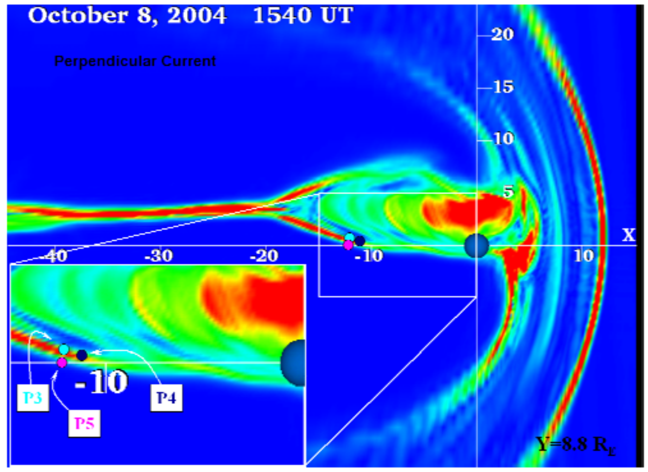

Figure 3B. Meridional cut (Y_{gsm}=+8.8R_E) of the perpendicular current in MHD simulations of substorms (El Alaouï, private communication). Y-type neutral sheets, current bifurcation and filamentation are expected in the tail, at scales from several ion gyroradii to ~1R_E. The inner edge of the plasma sheet is an important region for tail dynamics and will not have been visited at such scales by the THEMIS prime or by Cluster's polar orbiting satellites. The THEMIS extended mission in FY09-12 has the capability (e.g., Figure 2B, caption) and will have the needed separations to assess the properties and evolution of such currents in this critical region of space.

The substorm current wedge field-aligned current sheets are thought to form by a diversion of the cross-tail current sheet. This implies that the two current systems are linked and their coupling mechanism is a key question in magnetotail physics. Simulations show that the dominant term in field-aligned current sheet generation at substorm onset is the radial/vertical pressure gradient. Studies of both current systems and their link necessitate simultaneous radial and Z-separated probes, at scales comparable to the current sheet thickness, on the order of 100s to 1000s of km. The extended THEMIS baseline mission provides for the first time such separations at progressively finer resolution (and resolving power) over three tail seasons during its lifetime. The field aligned current produced by the diversion of the cross-tail current can be measured spatially, and mapped to the auroral altitudes. Numerous FAST over passes of THEMIS's ionospheric footpoint, such as the one captured on Mar 23, 2007 (Fig 6A) are uniquely suited to ascertain the continuity of the field aligned current over the THEMIS GBOs, and determine its effects in the ionosphere.

The extended baseline mission is the first mission in the equatorial magnetotail to provide simultaneous radial and vertical separated measurements of current sheets and pressure gradients. By exploring scales ranging progressively from field line curvature (1000s of km) to ion gyroradius size (100s of km), the extended THEMIS mission will lead to new discoveries pertaining to the current carriers that support the magnetotail, and the evolution of the dominant current systems during active times.

3.1.2 Dissipation of fast flows. High-speed flows carry plasma, energy and magnetic flux Earthwards. The sharp (~ several thousand km) gradients in flow speed at the edges of flow channels generate currents, and the associated magnetic field perturbations have been observed by Cluster at 15 to 19 R_E from Earth. The flows ought to stop at locations where the flux tubes they transport have entropies comparable to those of the surrounding media. This is expected to happen near the transition region between dipole-like to tail-like fields, around 7-12 R_E from Earth. Single point measurements from Geotail at 10-15R_E distance indicate that the flow energy is transferred into wave energy, particle heating, turbulence, or generation of field-aligned currents. But how does this interaction of the incoming fast flows and dipolar plasma take place? Understanding the deceleration of the incoming plasma by the forces that act on it requires careful modeling of the magnetic field topology and the specific entropy, $pV^{5/3}$ (p is plasma pressure and V the volume of a unit magnetic flux tube) of the flux tubes. Observations of pressure and magnetic field line curvature from satellite pairs simultaneously at radial and Z_{gsm} separations are thus needed. Such observations will be available for the first time in this key region of space with the THEMIS extended mission. With the help of LANL, GOES and Geotail (when available at distances 10-15R_E) the results can be extended both Earthward and tailward, albeit at lower fidelity due to the larger spacing between and the single point nature of measurements from other satellites. *The THEMIS extended mission will use its radial and Z-separated probes at 7-12 R_E to model the plasma sheet flux tubes, their entropy content and the forces acting upon them to determine the dynamic interaction of the fast flows with the ambient plasma.*

Turbulence is expected to play a role in flow energy dissipation, as it transfers power to smaller scales where kinetic processes take effect. Cluster studies of mid-tail turbulence indicate that the inertial range terminates at spatial scales near 0.5 R_E, where there is a break in the power spectrum. Similar studies, to be carried out using the THEMIS prime mission are also expected to show that the dissipation scale resides in the range between the ion gyroradius and the field line curvature. Limited (single satellite) TC-2 observations in the region 10-12 R_E indicate that the anisotropy of turbulence has different scale-dependence than was observed by Cluster in the mid-tail region [Vörös et al., 2007]. This is not unexpected, since at the inner edge of the plasma sheet, the Earth's strong dipole field affects (brakes) the flows, whereas at Cluster distances the effects of Earth's dipole are less significant.. Unlike in the solar wind, where advected turbulence is a reasonable approximation, in the plasma sheet the field fluctuations evolve on temporal scales comparable to their travel times. Distinguishing between Doppler-shifted (spatial) and ambient (temporal) power (fluctuations) can only be done with multiple satellites. Multi-point observations over separation distances ranging from 0.1 to 1R_E are crucial for evaluating the dissipation range of plasma sheet turbulence and its role on conversion of flow energy to heating. *The extended THEMIS baseline mission will utilize its correlations and differences of particles and fields measurements at radially separated probes to determine the dissipation range of plasma sheet turbulence and its role in particle heating during fast flows.*

In summary, THEMIS will determine the nature and evolution of the dominant current system in the magnetotail, and the manner by which the inner edge of the plasma sheet and turbulence decelerate and dissipate fast flows in the near-Earth magnetotail.

3.2 Inner magnetosphere science

As preparations for NASA's RBSP mission continue, the inner magnetosphere (comprising Earth's ring current and radiation belts) is becoming the focus of concerted studies. In its prime mission (FY08/09) THEMIS will focus on determining whether radial diffusion or local wave acceleration is responsible for the rapid appearance of relativistic, "killer" electrons during of the recovery phase of storms. Prime mission orbits provide frequent (at 2-4hr recurrence) crossings of the putative source population at 9-12 R_E. By determining radial gradients in electron phase space density and the local wave power, the prime mission, will distinguish between these two candidate electron acceleration processes. Studies of small storms and substorms show that THEMIS can achieve this objective (see Figure 6B and Runov et al., TGRL). Since launch in February 2007 the THEMIS probes have observed only few small geomagnetic storms. Predictions: http://solarscience.msfc.nasa.gov/predict.shtml) indicate a sharp rise in solar activity throughout 2008-2009. Therefore, both THEMIS data and solar cycle forecasts suggest that THEMIS will have no problem achieving its radiation belt science objective during the prime mission.

For the extended phase (FY10-12), THEMIS proposes to build on knowledge gained from the prime mission regarding electron acceleration to address other key objectives pertaining to storm dynamics. Based on the last solar cycle, we expect to see about 30 major magnetic storms (Dst < -150 nT) during the extended baseline mission from 2010 to 2012. The mission will employ string-of-pearls configurations with along-track separations of several R_E during the dayside and tail seasons, but ranging from 2 R_E down to 100's of km during the dawn and dusk seasons. These separations are ideally suited to addressing the role of waves in storm time electron acceleration and loss, and the role of large electric fields for ring current development and evolution.

The most effective wave acceleration mechanisms of storm-time MeV electrons is likely resonance with VLF lower band chorus (through violation of the first adiabatic invariant) and resonance with ULF waves (through violation of the third adiabatic invariant). ElectroMagnetic Ion Cyclotron (EMIC) waves have been identified as a potentially dominant loss process (through loss-cone scattering by Doppler shifted cyclotron resonance). THEMIS is well-instrumented to study VLF (Fig. 3B), ULF and EMIC (Fig. 3C) wave-related electron acceleration/losses in the time domain.

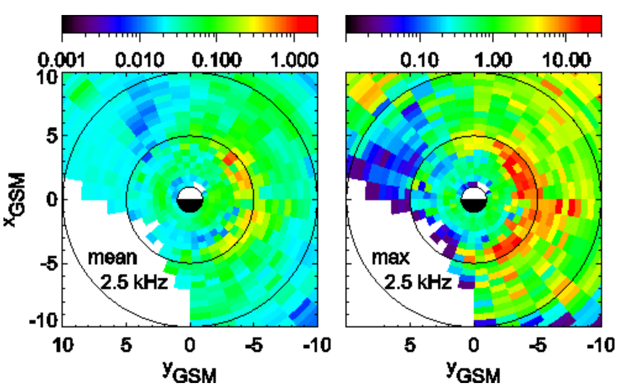

Figure 3C. Mean (left) and peak (right) wave amplitudes in VLF range (1.3-3.7kHz) observed by THEMIS C, D, E during coast phase (Cully et al., TGRL). WB data collection at 8kSample/s allows studies of chorus electron acceleration, in conjunction with electron data from the SST instrument.

Traversals of the radiation belts by probes over 0.1-2R_E scales will distinguish the spatial extent of the waves in L-shell from the temporal growth of the waves due to the presence of (measured) free energy sources. Longer term changes in radiation belt morphology due to the stochastic combination of ULF (Pc3-5 and EMIC) and VLF acceleration and loss processes are also possible with the SST through studies of the dynamics of radial profiles of electron phase space density up to energies of 900 keV. This is especially true in combination with ancillary measurements from Cluster, SAMPEX, LANL and GOES satellites. THEMIS studies will enable analysis of key wave-particle interaction processes, which drive radiation belt dynamics. Local sources on multiple probes in a unique, string-of-pearls configuration will extend the analysis of radial phase space density from the prime mission, and prepare the field for the advent of RBSP during the ascending phase of the next Solar Cycle.

In conjunction with ancillary observations, THEMIS will determine the role of wave-particle interactions and the spatial distribution and temporal evolution of particle distributions and processes affecting radiation belt flux variations during geomagnetic storms. THEMIS is a precursor to RBSP.

The large electric fields that occur within the inner magnetosphere during geomagnetic storms are intimately linked to magnetospheric plasma flows, field-aligned currents, and the transient magnetic field reconfigurations that occur during substorms and the ring current closure through the plasmaspheric trough. Strong storm-time electric fields often result in sub-auroral polarization drifts, erode the plasmasphere and create plasma plumes that stretch outward to the dayside magnetopause. Accurate electric field models are essential to model the supply of plasma sheet particles to the inner magnetosphere and the configurations of the plasmasphere and ring current. State-of-the-art magnetospheric electric field models are still inadequate for describing storm time inner magnetosphere: The Volland-Stern model shows electric fields increasing with radial distance from Earth; yet Rowland and Wygant [1998] find a broad local maximum between L=3.5 and L=6.5.

Separations ranging from 0.1-2R_E are needed to unravel the sharp density and electric field gradients on the edges of the plumes and to study how substorm electric fields and may propagate into and affect the ring current region. The equatorial, string-of-pearls strategy of the THEMIS extended baseline mission is ideal for mapping the quasi-static storm-time electric field, determining its spatial extent and long-term evolution, and (in conjunction with ground-based observations) addressing the relationship between strong fields observed in space and the sub-auroral ionosphere. Working with the mid- and low-latitude Millstone Hill, SuperDARN, and Arecibo radar teams of ionospheric densities and electric fields, ground-based GPS observations of ionospheric densities, and FAST's <2hr cadence crossings of inner magnetospheric latitudes, often above these radars, we expect to establish the relationships between these strong electric fields at their source, at THEMIS altitudes, and on the ground.

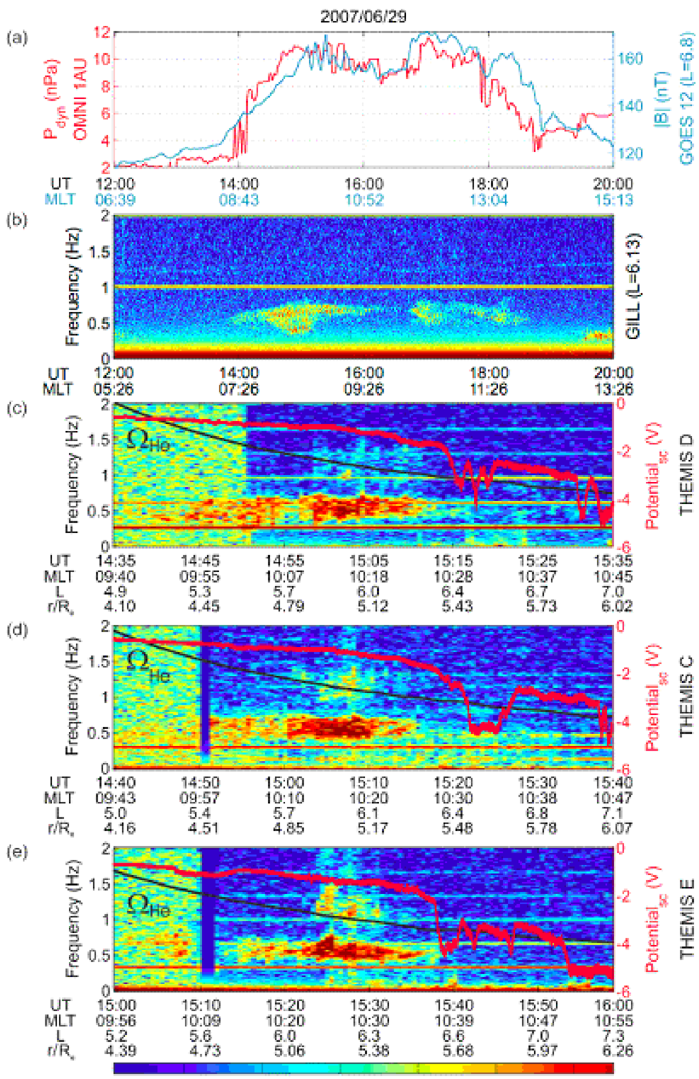

Figure 3D. An EMIC event, on Jun. 29, 2007, seen by THEMIS TH-C, D, E from a string-of-pearls formation. All probes consistently recorded Pc1 magnetic field fluctuations at L shells of 5 - 6.5. THEMIS determines the radial extent in the magnetosphere to be ~1.3 R_E. The coherent EMIC waves were seen slightly further out by each subsequent probe pass, but in each case werebounded at high-L by a decrease in density, as determined by probe potential (Usanova et al., TGRL). Such formations, key for resolving spatio-temporal ambiguities of wave-particle interactions will only be possible again during the THEMIS extended phase.

Finally, THEMIS's multi-year coverage affords an opportunity to develop a true empirical global electric field model pertinent to the storm-time inner magnetosphere, which will be crucial for analysis and modeling of data in the RBSP era. *THEMIS will determine the role of large storm-time electric fields in storm-time ring current evolution. In conjunction with ground-radar & FAST observations, THEMIS will determine how they couple to the ionosphere.*

3.3 Dayside science

During coast phase, in the summer of 2007, THEMIS traversed the magnetopause in a string-of-pearls configuration, at inner probe distances of 100s to 1000s of km and outer probe distances of 1-2R_E. These separations revealed the remote (Figure 3E) and internal (Figure 6D) structure of FTEs, and the asymmetric nature of the Hall electric field at the magnetopause (Figure 3F on p. 11).

During the dayside portions of the prime mission (D1 and D2, see Table 1A) probes P3,4 and 5 will study the equatorial magnetopause in the X-Y_{gsm} dimension at 0.5-2R_E scales and distinguish between FTEs, pressure pulses and other phenomena over under a variety of upstream conditions. In the extended mission, (D3 and D4 in Table 1A) probes P3,4,5 will be poised to address critical, unanswered questions pertaining to the structure of the current layer in the equatorial magnetopause, from smaller scale separations and different vantage points. Near the subsolar magnetopause, from separations comparable to the thickness of the magnetopause (~1000 km) in the radial direction and ~200-3000km in the Z direction THEMIS will be ideally positioned to study the microscale structure of the magnetopause current layer, in particular asymmetric reconnection, magnetic islands, and particle energization within them.

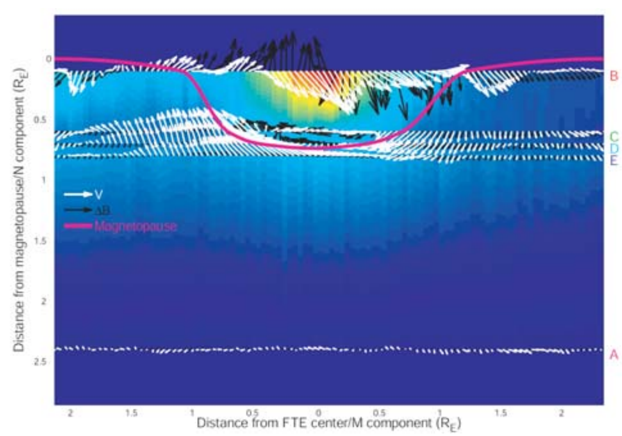

Figure 3E. Flows (white arrows), magnetic perturbations (black arrows), boundary location and total pressure (color) during an FTE traversal by THEMIS (Liu J. et al., TGRL).

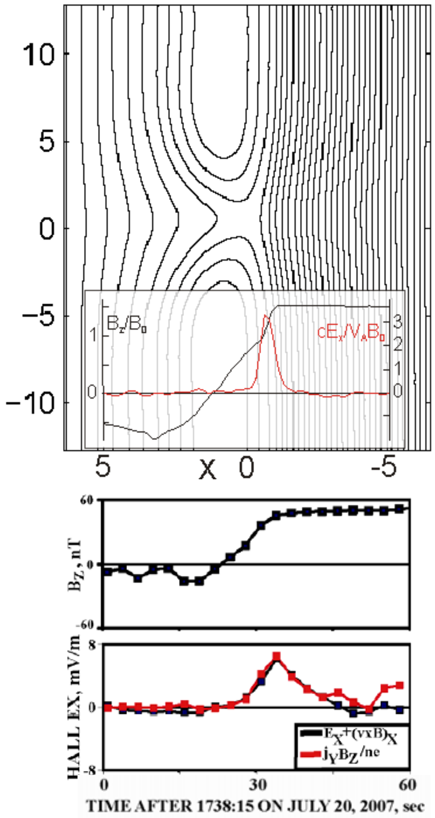

Figure 3F. THEMIS-C observations of electric fields at the magnetopause (bottom, Mozer et al., TGRL) agree well with predictions of Hall electric fields in models for asymmetric reconnection (top, Pritchett, private communication). Here X points sunward and Z points along the magnetospheric field. While in the coast phase string of pearls formation, THEMIS had no chance to simultaneously observe the outflow and inflow conditions. The extended mission will provide the vertical separations along the magnetopause needed for such investigations.

Despite its prevalence, much less is known about the asymmetric reconnection that occurs on the dayside magnetopause, than the idealized, symmetric reconnection. Recent simulations indicate that the two differ greatly in terms of reconnection rates, X-line and stagnation point locations, outflow densities and outflow velocities, the outflow opening angle and the shape of transient reconnection bulges (Cassak and Shay, 2007). Curiously, models predict that enhanced guide fields stop asymmetric reconnection for certain orientations. All these predictions can be tested using closely-spaced multi-point measurements during the extended baseline mission. Inflow parameters will be monitored carefully to determine the precise effect of the newly discovered (McFadden et al., 2008) persistent cold plasmaspheric plume layer in the afternoon magnetopause. This is occasionally seen inside FTEs and therefore expected to partake in dayside reconnection. *THEMIS, with its comprehensive instrumentation and from a completely new vantage point, i.e., radially and Z-separated probes at scales ranging from ion-inertial lengths to small FTE-sizes ($1R_E$), will address key questions regarding the nature of the typical, asymmetric reconnection at the subsolar magnetopause.*

The THEMIS extended mission will be uniquely suited to address questions concerning the role of FTEs/magnetic islands in particle energization. THEMIS will categorize the dimensions and occurrence patterns of FTEs for comparison with the predictions of theory and modeling. Models indicate that efficient electron acceleration requires interaction of electrons with multiple islands. Determining how small scale FTEs (bubbles) grow, coalesce, and decay is important because according simulations, this may be the key to understanding how reconnection accelerates electrons to energies far above those associated with the large-scale reconnection flows [Drake et al., 2007; Pritchett, 2006]. Fermi electron acceleration in contracting magnetic islands yields power law spectral indices consistent with soft magnetospheric and hard coronal observations. In situ observations at Earth can help us understand remote observations of particle acceleration in solar and astrophysical environments.

From multiple points along the nominal FTE motion (Z) and across the magnetopause (X), and with ideal separations, the THEMIS extended mission will probe the internal structure of FTEs and determine the degree of particle energization as a function of island size and/or island coalescence, as well as the guide field strength.

In summary, the baseline THEMIS extended mission will provide critical observations needed to describe the physics of asymmetric reconnection and particle acceleration at the dayside magnetopause.

4. ARTEMIS (P1 and P2)

The "Acceleration, Reconnection, Turbulence, and electrodynamics of Moon's Interaction with the Sun" (ARTEMIS) mission addresses the dynamics, scale size, and energy balance of distant tail particle acceleration and reconnection processes, solar wind and magnetotail turbulence, and the yet unknown kinetic properties of the lunar wake from multiple vantage points. ARTEMIS is a mission of discovery in support of the Heliophysics Great Observatory and the Vision for Space Exploration. Its lower energy particle measurements and comprehensive fields instrumentation complement LRO's higher energy measurements from the CRaTER instrument, and characterize the lunar electrodynamic environment to help interpret LRO's data. In addition, ARTEMIS serves as an accurate, near-Earth solar wind monitor ~ 80% of the time, working synergistically with STEREO's remote sensing of Solar variability and ACE's and Wind's early warning capabilities. The remainder of the time, ARTEMIS works in tandem with Geotail, Cluster, and the extended THEMIS baseline mission to study effects of near-Earth reconnection (plasmoids, flux ropes) in the distant magnetotail.

ARTEMIS is the first multi-probe mission with the comprehensive field and particle instrumentation required to study the distant tail and the lunar wake. Its two probes, P1 and P2, will determine the shape and extent of plasmoids and reconnection lines, and expand our understanding of solar wind and plasma sheet turbulence by surveying these phenomena over hitherto unexplored spatial scales. Finally, with two probes, ARTEMIS will be able to disentangle temporal and spatial variations of the lunar wake and their relationships to upstream solar wind conditions.

History: Late into the THEMIS mission development cycle we recognized that Earth shadows exceeding the bus design limit would threaten P1, P2 during their third tail season (one year after the prime mission was over). Additionally, P1 and P2's line of apsides would be 54^o and 27^o off of those of P3,4,5's, rendering their conjunctions less than optimal. P2's shadows could be reduced, if it were brought to a sidereal day period, 12R_E apogee orbit. However, by placing P1 and P2 into stable lunar orbits, their potential for scientific discovery is maximized, while the risk of freezing is avoided. This formed the genesis of the ARTEMIS concept, and a science team was formed. Orbits have been optimized for maximum science in collaboration with JPL since 2005, and were vetted with the team on three THEMIS Science Working Team meetings. Two technical reviews held at GSFC and at JPL further strengthened the technical concept.

Mission Phases: Figure 4A shows the ARTEMIS mission phase sequence. In each mission phase, as the moon visits the Tail, Solar Wind and Wake once per 28 days, the two probes measure these regions from an unprecedented variety of probe separations. After trans-lunar injection (*TLI phase*), P1 and P2 are captured onto opposite Earth-Lunar Libration points LL2 and LL1 respectively. Hovering in 15 day-period "Lissajous" orbits results in 10-20 R_E separations (*LL1,2 phase*), both along and across the Sun-Earth line. After 3 months P1 is brought onto the same side of the moon, on LL1, resulting in smaller, 5-10R_E separations (*LL1 Phase*). After another 3 months, both probes are inserted into stable, 1500km x 18000km, equatorial, ~1-day period lunar orbits with separations of 500 km-5R_E (*LO Phase*). P1 is on a retrograde and P2 on prograde orbit, resulting in a fast, 360^o relative precession during the 17 months of this phase. It is evident that the probe separations become progressively shorter as the probes move from one mission phase to another. ARTEMIS retains some flexibility in continuing its trade studies (see section 5) through late 2008 in anticipation of new findings expected from the first tail season and ancillary assets materializing at the Moon.

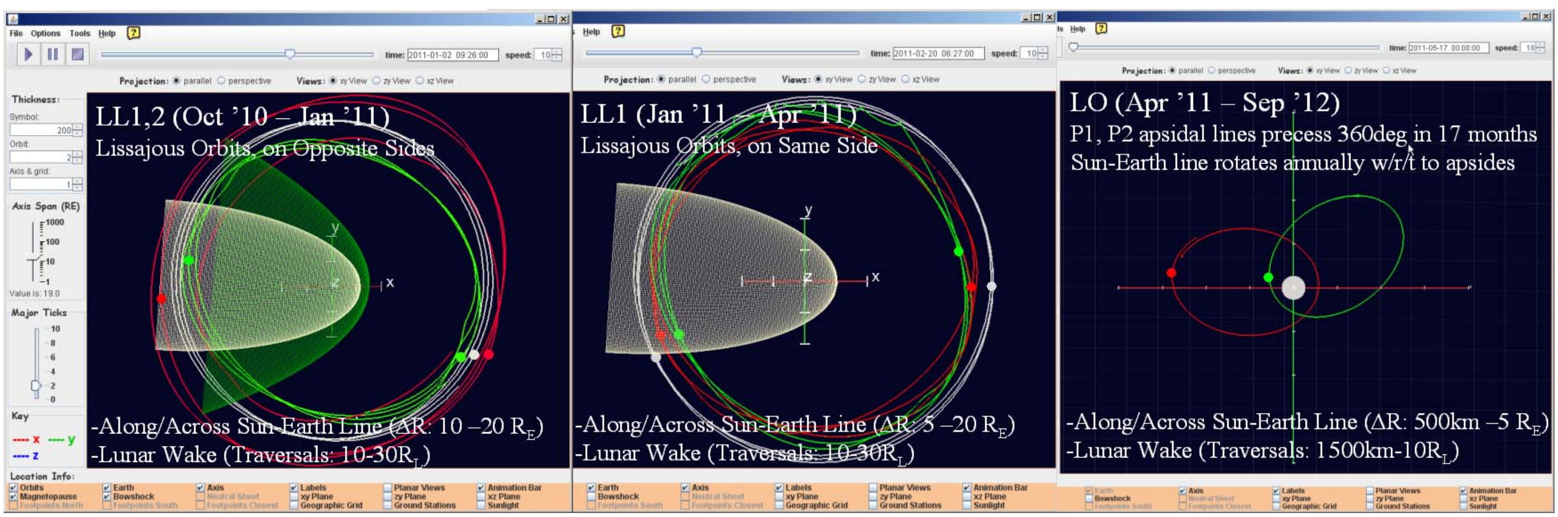

Figure 4A. ARTEMIS by phase (Phases LL1,2 and LL1 are shown in GSE coordinates. Phase LO is shown in Selenocentric Solar Ecliptic, SSE, coordinates. Acronyms in Table 1A). P1 is red, P2 is green and the moon gray. Mission phases are designed to permit progressively smaller inter-probe separations in all regions visited. These orbits are publicly available for plotting at: http://sscweb.gsfc.nasa.gov/tipsod For probes P1 and P2 select: Z1_artemis and Z1_artemis; for the moon select: "Moon".

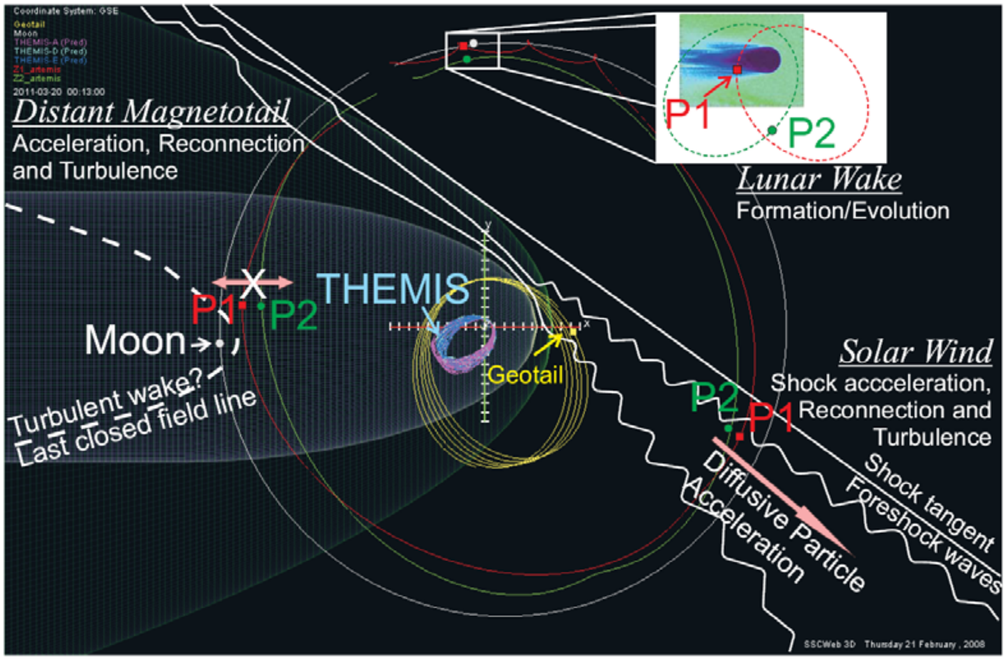

Figure 4B. ARTEMIS depicted by science region. Every 28 days probes P1 and P2 traverse the magnetosphere, the solar wind and (multiple times) the lunar wake, addressing key questions in Heliophysics and in the Vision for Space Exploration.

Figure 4B shows the three regimes visited by the probes in lunar orbit and the science objectives within them. ARTEMIS addresses questions related to (i) Acceleration, Reconnection and Turbulence in the magnetosphere; (ii) Acceleration, Reconnection and Turbulence in the Solar Wind and (iii) the Electrodynamics of lunar environment. Specifically:

4.1 In the magnetosphere.

Tantalizing, but brief passes of the "distant" magnetotail by ISEE-3, Geotail, Galileo, and Wind demonstrated that the region hosts diverse, fundamental plasma physics phenomena: quasi-steady reconnection resulting in heated plasma jets, beams of energized particles, twisted and/or unusually cold and dense plasma sheets and turbulence. The distant reconnection line is thought to reside at times at 55-65R_E from Earth, making the lunar orbit particularly interesting for global magnetotail circulation. The fundamental processes occurring there are common to other planetary and astrophysical systems (see Figure 4C). Additionally, the magnetotail at lunar distances is an ideal vantage point from which to study the integrated output from the near-Earth processing of stored solar wind energy in the form of heated/accelerated flows and plasmoids. ARTEMIS will study these phenomena for the first time both comprehensively and systematically, from the unique perspective afforded by its two identical probes.

In the magnetosphere, ARTEMIS will address:

- How are particles accelerated up to 100s of keV?
- What are the nature and effects of reconnection?
- What are the drivers and effects of turbulence?

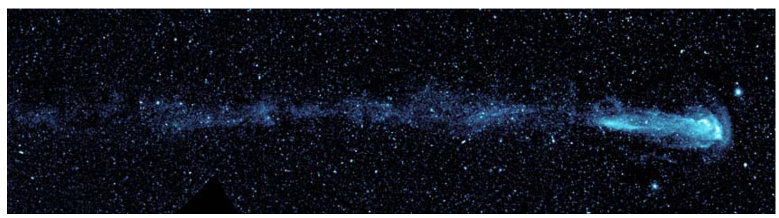

Figure 4C. Supersonic motion of Mira, a mass-shedding red giant moving through the interstellar medium, creates a thirteen light-year long tail. The tail-length to standoff distance ratios for Mira and Earth are comparable. Plasma acceleration, reconnection and turbulence are basic processes controlling the dynamics of that stellar object's tail, but only at Earth can we study them comprehensively using ARTEMIS's dual, well-instrumented probes. http://www.galex.caltech.edu/MEDIA/2007-04/

4.1.1 Particle acceleration. Simulations show that particles in reconnection geometries gain energy as they drift along X-lines, but can also be Fermi-accelerated in the collapsing bubbles surrounding O-lines. Wind observations in the distant magnetotail provide evidence for electron energization up to 300 keV [Øieroset et al., 2002]. Two-probe ARTEMIS observations of flows and magnetic fields are needed to discriminate between (and track the motion of) X- and O-lines [Eastwood et al, 2005a]. Comparing observations of particle distributions by the ESA and SST instruments at X- and O-lines with models, *ARTEMIS will distinguish between the two acceleration mechanisms and determine the maximum energy obtainable under a variety of external conditions.* Additionally, the factors controlling ion heating by tail reconnection are presently unknown. Simulations suggest that this heating is proportional to the inflow Alfvénic speed. The distant magnetotail is an ideal, pristine laboratory to study these phenomena: the absence of a near-Earth high-field obstacle there eliminates the possibility of heating by flow braking. Simultaneous inflow and outflow parameters are needed to ascertain the results of these models. *ARTEMIS will obtain simultaneous measurements of the reconnection inflow and outflow conditions to determine the mechanism of ion heating in the distant tail.*

4.1.2 Reconnection: Its nature and effects. ISEE-3, Geotail, and Wind observations built a statistical picture of large-scale quasi-steady reconnection line in the distant magnetotail, which appears to be bowed, with closest approach to Earth at the center of the magnetotail (Figure 4B). Some simulations indicate that both the north-south and dawn-dusk interplanetary field components control the cross-tail extent of the X-line. In the absence of multi-satellite observations we do not know the conditions favoring point- versus line- reconnection and the instantaneous shape of the distant reconnection line. Case and statistical studies combining observations by the two ARTEMIS probes will determine the occurrence patterns, orientation, and length of reconnection lines in the magnetotail at lunar distances as a function of solar wind and geomagnetic conditions.

Most of the plasma jetting from reconnection in the distant tail does not reach the near-Earth plasma sheet [Øieroset et al., 2004]. We do not know presently whether field line tension, boundary layer waves, flank-ward diversion, or plasma sheet turbulence decelerates these flows. Conversely, transient reconnection both in the near-Earth, as well as in the mid-tail regions, ejects anti-sunward moving plasmoids and Earthward moving flux ropes (see Figure 4D). Plasmoids are expected to accelerate once reconnection reaches the last closed field line, but may decelerate when moving in the Earthward direction. In the absence of multipoint measurements, even the most basic characteristics of fast flows and plasmoids in the tail remain poorly understood. Understanding these phenomena is important for determining how the distant tail reconnection process affects global flux and energy circulation, as well as the amount and extent of particle energization in the near-Earth environment.

Radial separations of 1-10 R_E parallel to the Sun-Earth line enable the two ARTEMIS probes to track the evolution of high speed flows and plasmoids over short distances. ARTEMIS will work in conjunction with Geotail, Cluster and the extended baseline THEMIS probes, to determine the Earthward extent of sunward flows generated in the distant magnetotail and track the tailward motion of plasmoids generated by near-Earth reconnection. ARTEMIS will determine the conditions under and the means by which the latter structures accelerate and grow or

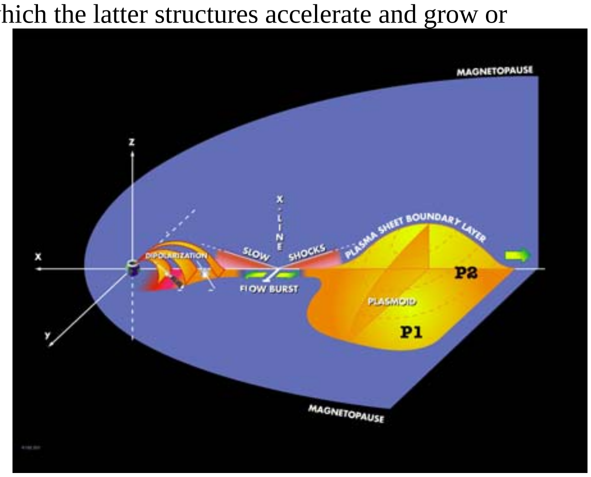

Figure 4D. Until ARTEMIS's distant tail, two-point observations, the flow burst and plasmoid cross-tail extent, shape and structure will remain no more than an artists' conception, based on ephemeral visits by single satellites. Simulations cannot provide definitive answers due to the inclusion of numerical or artificial resistivity.

decelerate and dissipate along the tail axis. Azimuthal probe separations enable ARTEMIS to determine the cross-tail extent, orientation, shape (using minimum variance analyses of the magnetic field), internal structure, and topology (using particle pitch angle distributions) of plasmoids.

ARTEMIS will define the characteristics and effects of reconnection in the distant magnetotail, from structural, magneto-hydrodynamic scales down to the ion gyroradius and ion inertial length scales. Together with Cluster, Geotail and the baseline THEMIS extended probes, ARTEMIS will define the evolution of reconnection jets and plasmoids from near-Earth to the distant magnetotail.

4.1.3 Turbulence: drivers and effects.

Turbulent dissipation is an effective mechanism for heating fluids and transferring mass, momentum and energy. Turbulence in the near-Earth region has been studied using Cluster [Weygand et al., 2007]. Here, the dissipation range is on the order of the ion inertial lengths or gyroradius (~few hundred km) and the correlation coefficients diminish to zero beyond scales of $3R_E$. But unlike at the near-Earth tail, where the flow fluctuations are small relative to the sound and Alfvén speeds (except in dynamic conditions), in the distant tail and the fluctuation flows are comparable to the sound and Alfvén speeds and therefore the fluctuations are dynamically and energetically important. Theoretical work and global simulations point towards magnetotail reconnection and velocity shears at the flanks as likely drivers of plasma sheet turbulence. Both drivers can affect energy circulation and particle transport within the magnetosphere. Characterizing the nature of these fluctuations, and determining their origin and dissipation is therefore important for global circulation. It is quite likely that the distant tail also exhibits an inertial range of turbulence at 1-10R_E scales and a dissipation range at 0.1-1R_E.

During periods of strongly northward IMF, the magnetosphere may close within lunar distance [Usadi et al., 1993], leaving a turbulent wake at greater distances. We seek to identify and differentiate this wake, unrelated to magnetospheric convection, from inner magnetospheric or low latitude turbulence. To determine the drivers and effects of turbulence, the spatial and temporal variations of plasma and magnetic field measurements over a wide range of solar wind conditions and scale lengths must be measured.

ARTEMIS's two-point measurements at separations of a few hundred km to several R_E in directions transverse to the Sun-Earth line, can pinpoint the origin of the turbulence (reconnection flows versus boundary layer shear). Electron pitch angle distributions with the turbulent flows will determine whether field lines are open or closed, thus differentiating between a turbulent wake behind a closed magnetosphere or internal magnetotail turbulence. Ion-scattering in thin current sheets or secondary reconnection centers in turbulent layers will be studied as potential avenues to turbulent heating. *In conjunction with upstream solar wind measurements from ACE and Wind, ARTEMIS will establish the external conditions for, and characterize the nature of magnetotail turbulence.*

Turbulence is also expected to result in significant diffusion of plasma across the magnetopause boundary. Observations of a cold dense plasma sheet during northward IMF indicate that solar wind / sheath plasma has ready gains to the magnetotail even when no reconnection is expected on the dayside magnetopause. Such "cold dense plasma" is important for space weather because it intensifies the ring current under storm commencement immediately following strongly northward interplanetary fields.

The non-linear evolution Kelvin Helmholtz instability at the magnetopause may result in turbulent diffusion rates sufficient for solar wind plasma to cross the magnetopause boundary, and create the aforementioned cold dense plasma sheet. ARTEMIS's cross-tail conjunctions will detect the rolled-up waves driven by the Kelvin-Helmholtz instability and outward-oriented gradients in the plasma density expected for diffusion. Alternative hypotheses, e.g., solar wind entry due to high latitude reconnection, will be tested through searching for abrupt shear boundaries between recently reconnected and still open magnetic field lines. Wind and ACE data will be used to determine the upstream conditions and classify event occurrence patterns. ARTEMIS will determine the effects of turbulence on plasma sheet heating and mass circulation. Comparing these results with THEMIS's baseline studies at distances inside of $12R_E$ and Cluster's findings in the inner magnetosphere, plasma sheet turbulence and its effects can be studied as a function of magnetotail distance. *ARTEMIS will characterize plasma sheet turbulence over a previously unexamined range of spatial scales. It will determine, when, where and how turbulence originates in the magnetotail at lunar distances; and what its effects are for tail dynamics and magnetospheric circulation.*

ARTEMIS will spend four days per month, from October 2010 to September 2012, in the magnetotail. P1 and P2 will observe the plasma sheet from 20 to 30 hours per month, each collecting 2400hrs of magnetotail data, including 500-700hrs in the plasma sheet; more than enough to characterize this region of space and define its variability at unprecedented time resolution (burst mode) and with well inter-calibrated instrumentation. *From vantage points spanning kinetic to global phenomena, ARTEMIS will revolutionize our understanding of particle acceleration, the nature and effects of reconnection and the drivers and effects of turbulence in Earth's distant magnetotail.*

4.2 In the Solar Wind

Spending more than 80% of its time in the solar wind, ARTEMIS provides a unique opportunity to address long-standing questions concerning the physics of the solar wind and collisionless shocks. In the solar wind, ARTEMIS will determine:

- How particles are accelerated at shocks
- The nature and extent of low-shear reconnection
- The properties of the inertial range of turbulence

4.2.1 Particle acceleration: Collisionless shocks are sites for particle acceleration in a variety of astrophysical and heliospheric environments. ARTEMIS observations of both solar wind shocks and the Earth's foreshock will be used to address important questions regarding particle acceleration and heating.

Solar Energetic Particle events with energies from 10's to 100's MeV, are one of the prime interests of Heliophysics. The largest, so-called "gradual events", occur at oblique interplanetary shocks and require a seed population of 50 keV – 5 MeV particles. It has been proposed that such particles are locally produced by shock undulations of a few hundred ion inertial lengths, i.e., a few R_E. Figure 4E shows the structure of an interplanetary shock inferred from in situ measurements on Wind [Bale et al. 1999]. Multipoint measurements of the average Rankine-Hugoniot conditions (e.g., the shock-normal angle, θ_{Bn} and the Alfvén Mach number, M_A), and the spatial scales of the curvature are needed to verify this hypothesis.

At separations ~1-20 R_E, ARTEMIS's two probes will determine shock jump conditions and identify shock undulations for comparison with models of particle acceleration at shocks, thus answering key questions regarding the seed population of solar energetic particle events.

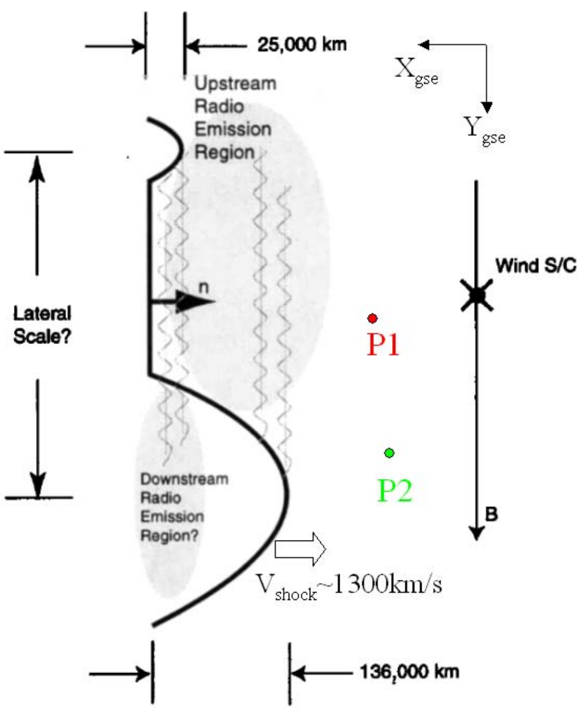

Figure 4E. ARTEMIS, P1, P2, will make the first two-point measurements of shock undulations to determine how the 50keV-5MeV seed population for Solar Energetic Particles is accelerated at such structures, as predicted by theories. Shock undulations were inferred by Wind (as seen adapted from Bale et al., 1999) but never actually observed.

Earth's bow shock and foreshock are also excellent locations for studying the fundamental processes of particle acceleration [e.g., Eastwood et al., 2005b]. A small fraction of the solar wind ions incident on Earth's bow shock is reflected and accelerates to energies of tens of keV. These particles then stream into the upstream region along magnetic field lines, generate waves, and the waves both scatter and continue to accelerate the particles to energies of hundreds of keV.

At lunar distances, where diffusively accelerated particles were first observed by the Apollo sub-satellites, the acceleration process continues at rates that depend on the spacecraft depth and distance to the point of tangency, as well as on upstream conditions. With distance from the bow shock wave amplitudes diminish, particle fluxes fall off at rates that diminish with increasing energy, and pitch angle distributions vary from isotropic to streaming. At ISEE-3 distances, 200 R_E upstream, observations indicate only streaming particle populations, as both scattering and acceleration has ceased. Single-spacecraft observations just outside the bow shock indicate that energetic ion flux e-folding distances are around 3.2 ± 0.2 R_E at 10 keV, but a recent two-spacecraft Cluster case study measured the e-folding distance to be an order of magnitude smaller: 0.5 R_E at 11 keV. The reasons for disagreement remain unclear. What is certain is that two-point measurements provide a far more reliable measurement of the e-folding distance, and that experimental tests of quasi-linear theory of diffusive acceleration at the Earth's bow shock have not yet been carried out.

ARTEMIS's direct inter-probe comparisons will provide a wealth of data regarding e-folding lengths over key distances (0.1 to 20 R_E). Their orbits sample the foreshock at various distances from the tangent line and solar wind conditions. Using ARTEMIS burst mode collection, triggered by crossings of the electron foreshock and bow shock, the plasma instruments will return the electron distribution functions needed to identify the electron foreshock beams to establish connection geometries; while high time resolution 3-D electric field observations will aid our understanding of how those beams are created. Results will then be compared with pitch angle distributions and wave amplitudes to validate or improve our theoretical understanding. Geotail, when properly situated, will help establish the homogeneity of the upstream wave field, and allow correlation lengths parallel and perpendicular to the field to be studied routinely, without the confounding effects of upstream variability. *ARTEMIS will accurately characterize the properties of diffusive particle acceleration at the foreshock.*

4.2.2 Reconnection: Recent observations of reconnection "exhaust" regions have led to the identification of reconnection lines extending hundreds of Earth radii in the solar wind [Phan et al., 2006]. Such events enable detailed studies of reconnection under well-characterized conditions for comparing with simulations and theory. Examples reported thus far were accompanied by a large magnetic shear resulting in a wide exhaust fan. Lower shear cases of solar wind reconnection are interesting and far more common, but have yet to be reported due to the narrowness of the exhaust fan, which makes them more difficult to detect with the typical cadence of other solar wind monitors. High time resolution *plasma* measurements are essential to detect the narrower exhaust regions of low-shear reconnection. ARTEMIS's high time resolution accurate plasma moments and spin fits, as well as its Fast Survey and Burst mode collection, enable studies of the plasma structure within low-shear reconnection in the solar wind. Two-point ARTEMIS observations permit accurate, independent determination of shock normals at the exhaust and of the scale length of the reconnection region over 10-20R_E scales. Together with high-time resolution plasma measurements from Wind (Figure 4F), and ancillary ACE and Geotail magnetic field data we can determine the extent of these reconnection lines at even larger scales (>100R_E). *ARTEMIS's two probe high cadence plasma measurements, both alone and combined with ACE, Wind and Geotail, enable fundamental studies of the most common, low-shear reconnection in the solar wind over scales ranging from tens to hundreds of R_E.*

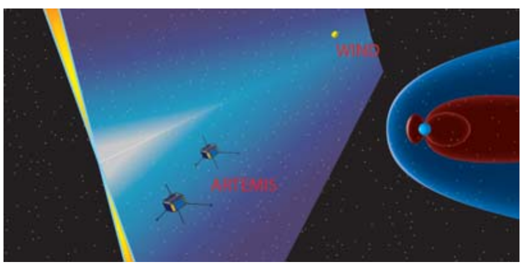

Figure 4F. ARTEMIS P1 and P2 equipped with high-resolution plasma measurements will explore the properties of the low-shear reconnection exhaust, over scales of tens of R_E, and with WIND up to >100R_E.

4.2.3 Turbulence: The solar wind is an excellent laboratory for the study of turbulence. Understanding the properties of the inertial range is important for modeling solar wind evolution through the Heliosphere, and for providing constraints on kinetic theories of energy cascade and dissipation in space plasmas in general. Reliable knowledge about the correlative and Taylor scale values allows the effective magnetic Reynolds number in the solar wind to be determined. Only recently have multi-spacecraft measurements been used to examine turbulent fluctuations across space without the assumption of "frozen-in" flow. Fortuitous conjunctions between existing satellites were used to study scales above 20R_E, and Cluster was used at distances less than 1R_E (dissipation range) to study the magnetic correlative and Taylor micro-scale lengths. The crucial range, however, of the turbulent energy cascade at 1-20R_E has not been studied due to lack of appropriate satellite conjunctions. One intriguing finding from previous studies is that the correlative scale varies with respect to the mean magnetic field direction but the Taylor scale remains relatively constant. It is important to investigate if this finding extends over the full range of inertial cascade of turbulence, because the turbulence anisotropy affects acceleration and propagation of cosmic rays, and solar wind heating. Artemis will make high quality, prolonged, two-point measurements of the pristine solar wind with well inter-calibrated instrumentation. It will provide the first measurements over the previously unexplored inertial range and through the dissipation range, without the need to invoke the Taylor approximation. *ARTEMIS will determine the properties of turbulent cascade in the inertial regime and how critical turbulence scale lengths vary under different solar wind conditions.*

The energy contained in the turbulent cascade is deposited in the dissipation range. The power spectra of electric (E) and magnetic (B) fluctuations can be used to determine the properties of the dissipation process. E & B spectra have the same index in the inertial range, but diverge at small scales (high frequencies) in the dissipation range. E & B spectral ratios can be used to determine whether the turbulent energy is deposited into the whistler mode or the Alfvén/ion-cyclotron mode. Comprehensive 3-D DC electric and magnetic field observations will determine for the first time the relative importance of these two wave modes in the dissipation of collisionless plasma turbulence as a function of solar wind conditions. *ARTEMIS will complete past surveys of dissipation turbulence in the solar wind by providing observations over a previously unexamined range of spatial scales with unique and well intercalibrated instrumentation.*

4.2.4 Solar Wind Monitoring: ARTEMIS will be an excellent monitor of solar wind conditions for Heliophysics missions. Especially when near the Sun-Earth line, ARTEMIS will be closer to the Earth than ACE or Wind and provide reliable observations with less uncertain time delays. THEMIS will define the lunar environment, including radiation hazards in the solar wind, magnetotail lobes, and plasma sheet on a case and statistical basis. *If requested, ARTEMIS can serve as a space weather beacon.*

In summary, in the solar wind ARTEMIS will: determine how the energizartion of the seed population of solar energetic particles and diffusive shock acceleration operate, determine the nature and extent of the most common, but elusive, low-shear reconnection, and will characterize the properties of inertial turbulence (through the dissipation range) from two-point measurements with identical, well inter-calibrated instrumentation.

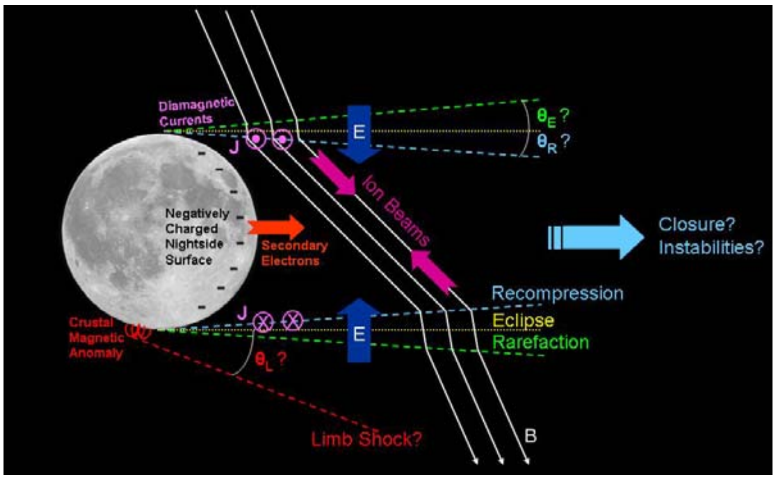

Figure 4G. ARTEMIS, with its full complement of charged particle, magnetic and electric field, and wave measurements, can provide multi-point measurements of the wake over a wide range of downstream distances for varying solar wind conditions and to address the wide array of phenomena that occur in the lunar wake.

4.3 At the Lunar Wake

The interaction between the solar wind and the Moon forms a wake on the anti-sunward side of the Moon. The Moon is essentially non-magnetic, non-conducting, and has no ionosphere, so most solar wind plasma is absorbed on the dayside, leaving a plasma void on the nightside [Schubert and Lichtenstein, 1974]. The interplanetary field passes through the Moon practically unimpeded resulting in no upstream shock. Lunar wake refilling is a fundamental process and the Moon's easily accessible environment provides a unique opportunity to understand a wealth of basic physics questions pertaining to plasma expansion into a vacuum (see Figure 4G). Knowledge gained at the Moon can be applied to plasma voids in torii around Earth, Jupiter, and Saturn and large objects in low earth orbit, e.g., the Space Shuttle, the International Space Station, and the Hubble Space Telescope.

Lack of *in situ* plasma measurements limits our understanding of the Lunar wake. Explorer-35 and the Apollo 15 and 16 sub-satellites, observed the wake extensively but carried limited instrumentation (low plasma resolution, in limited energy range). The Lunar Prospector (LP) mission had no ion detectors or electric field analyzers. Wind, Nozomi, and Geotail carried relatively complete plasma instrumentation, but made only a few passes. Extensive observations with the comprehensive ARTEMIS instrumentation offers a unique opportunity to:

- Determine the three dimensional structure and downstream extent of the lunar wake
- Identify the plasma acceleration processes and energetics in and around the wake
- Characterize wake formation and refilling under a wide range of solar wind and magnetospheric conditions.

4.3.1 Structure. Early studies treated the lunar wake as a magneto-hydrodynamic structure, i.e., a standing tangential discontinuity. As Explorer 35 identified no manifestation of the wake beyond 4 R_L (1 R_L = 1738 km), it was assumed that the lunar wake propagated as a magnetosonic disturbance, closing relatively rapidly within 3-10 R_L, depending on the interplanetary field orientation and Mach number, and that a trailing standing shock (never observed) would form at several R_L. However, Wind discovered a wake extending further, as much as 25 R_L [Clack et al, 2004] suggesting that the wake refills via an ion sonic mode. Wind observations of counter-streaming ion beams, large temperature anisotropies, and strong wave turbulence [Ogilvie, et al., 1996], as well as Nozomi observations of non-thermal ions and counterstreaming electrons indicate that the wake is far more kinetic. Figure 4H illustrates the predictions of a global hybrid simulation that a lunar wake extends well beyond 25 R_L downstream.

Asymmetries in wake structure are expected due to the IMF orientation being far from the wake axis or due to magnetosonic waves growing in the vicinity of crustal fields and propagating downstream. Observations do suggest asymmetric wakes, but with a single spacecraft they cannot be definitive. ARTEMIS's two probes will resolve spatio-temporal ambiguities, confirm relationships between wake structures and crustal features, determine how far downstream they propagate, and determine the degree to which they affect the interior of the wake.

Orbital configurations that place one or both of ARTEMIS' well-instrumented probes at the downstream wake will define the wake's extent and structure. Two-point measurements permit unambiguous determination of the asymmetries in the wake due to the perturbing influences of solar wind and crustal magnetic fields or other effects.

4.3.2 Energetics. Near the lunar limb, solar wind electrons diffuse rapidly across the low altitude wake boundary ahead of the slower ions, producing a charge separation electric field that slows the electrons and accelerates the ions. The resulting ambipolar electric field produces field-aligned beams of accelerated ions streaming into the wake from the flanks and can also cause pitch angle diffusion at the wake boundary [Nakagawa and Iizima, 2006]. Recent particle in cell simulations suggest that the charge separation between the 'electron cloud' and the trailing ion front can persist to several lunar radii downstream, forming a standing double layer with intense electric fields, as high as 0.1-1 V/m. These fields have never been measured directly before as no previous satellite carried the necessary DC electric field instrumentation. Hybrid simulations indicate that the density cavity should be filled by counter-streaming ion beams and large temperature anisotropies ($T_\perp > T_\parallel$), in general agreement with Wind observations [Travnicek et al., 2005]. *ARTEMIS will provide the first comprehensive measurements to determine both the large DC electric field at the lunar wake and its effect on the particle distributions.*

Secondary electrons from the surface provide another example of a fundamental acceleration process in the wake [Halekas et al., 2002]. LP commonly observed beams of secondary electrons produced at the lunar surface and traveling along magnetic field lines into the wake. It appears that these secondary electrons are generated at low energies at the surface, and then accelerated through the plasma sheath above the negatively charged nightside lunar surface. Typically these accelerated secondaries reach energies of only a few hundred eV. During magnetospheric plasma sheet passages and solar storms, however, the nightside surface charges up higher; at those times LP observed beams of upward-going electrons at several keV or higher. The beams have never been observed at higher altitudes and it is not known what altitude they reach before beam-plasma instabilities moderate them. The high fields and accelerated particles generated at the wake during solar events would have clear consequences for surface exploration or orbiting spacecraft.

The ion and electron beams and the temperature anisotropies produce waves. A broad wave spectrum was observed in and far upstream from the central wake on magnetic field lines connected to the wake boundary [Kellogg et al., 1996]. Simulations predict waves generated by two-stream electron instabilities in the central wake, bump-on-tail instabilities from particles passing all the way through the wake, ion acoustic-like beam instabilities that slow the ion beams in the central wake, flute instabilities, and low frequency electromagnetic turbulence with frequencies near the local proton gyrofrequency. This veritable zoo of plasma waves has barely been explored, and all the wave generation mechanisms and interactions between waves and particles remain unknown.

ARTEMIS's comprehensive suite of field and plasma instruments enables a detailed study of the plasma physics occurring within the lunar wake that leads to acceleration and energization. This includes the first DC electric field observations ever made in that region, direct observations of non-neutral plasma effects near the wake boundary, the extent of secondary electron beams, and their interaction with plasma refilling of the wake from the flanks.

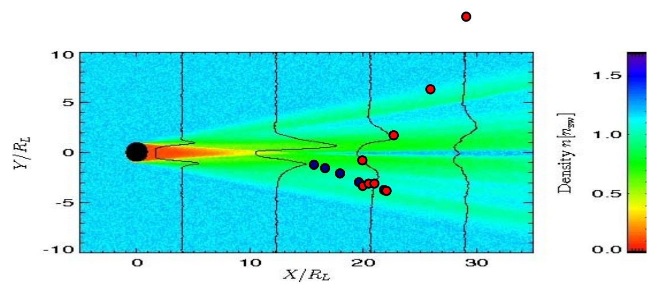

Figure 4H. ARTEMIS will provide an extensive survey of lunar wake properties as shown by the Lissajous phase probe crossings (red: P1; blue: P2) of a simulated wake (hybrid simulation by Travnicek, et al., 2005: kinetic ions; fluid electrons). Color is density relative to SW and anisotropy profiles are lines at select X distances downstream. Another ~<u>1000 crossings</u> occur inside of $10R_L$ during the lunar orbit phase of ARTEMIS (Figure 4A).

4.3.3 Statistics. The wake structure varies in response to external drivers. Statistical studies provide tantalizing hints on how the wake responds to changing or transient solar wind conditions, but incomplete instrumentation and orbital coverage has limited our knowledge of this response. *ARTEMIS will provide an unprecedented wealth of routine observations of the wake under a variety of solar wind conditions.*

Additionally, ARTEMIS will be able to show how transient solar wind features interact with the Moon itself (e.g. shocks).

In the magnetosphere, reconnection-accelerated fast Earthward flows emanating from beyond 60 R_E produce generally subsonic, sunward-oriented wakes at the Moon. These conditions can be highly variable, and are likely resulting in magnetospheric lunar wakes, with intense charging and particle acceleration conditions very different from those in the solar wind. To fully characterize those phenomena in support of ARTEMIS, 3D hybrid simulations, laboratory simulations and visualizations will be carried out to provide a global context for ARTEMIS's ground-truth observations. Lacking an unperturbed upstream monitor, previous single spacecraft observations of the lunar wake inside the magnetosphere have been difficult to interpret. With one probe in the unperturbed flow and the other in the wake ARTEMIS will make the first comprehensive observations of the lunar wake interior to the magnetosphere and fully characterize its formation, physics and particle acceleration within it. *ARTEMIS will provide the first detailed measurements of the lunar wake plasma environment within the terrestrial magnetosphere.*

5. Science Optimization Trade Studies

The THEMIS team embarks on the two-probe ARTEMIS mission with full confidence in its plans, but also a solemn commitment to optimize the science return for the Heliophysics discipline. The team will therefore not miss the opportunity to conduct technical feasibility and orbit studies of alternative strategies employing P2's available propellant margin. Pending analysis of results from the first THEMIS tail season, it may become apparent that P2 would prove most beneficial flying in formation with P3,4,5 or with one of several other lunar missions currently in proposal phase substituting for P2 at the moon. At present, these possibilities seem remote, but the THEMIS team remains open to alternate scenarios in consultation with the community and NASA/HQ.

6. Results to date

As indicated in the three examples given below, the THEMIS mission is as ideally suited to address topics from 100's – 1000's of km separations during its extended phase as it is to address its prime objectives with macroscale separations. (Note: P1-5 are referred to by their letters, based on probe assignments which occurred early in the commissioning phase (P1=TH-B; P2=TH-C; P3=TH-D; P4=TH-E; P5=THA).

6.1 Westward traveling surge: space signature

Prior to exiting the tail in 2007, and only a month after its launch, the full suite of instruments on the THEMIS spacecraft (with the exception of the undeployed EFI) captured their first substorm. The unique, string-of-pearls configuration allowed the first detection of the substorm westward traveling surge signature in space (Figure 6A). The Westward expansion speed in space of ~250 km/s matched the inferred expansion speed of the aurora in space as determined from auroral images. Using the finite gyroradii of energetic particles, Angelopoulos et al. (TSSR) remotely senses the expansion speed and orientation of the heated plasma at the three middle probes. The local expansion speed was 75 km/s away from the equator and agreed with the time delays of all key signatures on those probes: the Earthward flow burst, a magnetic field dipolarization and an injection of energetic particles (see Figure 6A). The expansion speed enables estimates of the field-aligned current direction, spatial extent, and intensity. The field-aligned currents at THEMIS' altitude are consistent with typical currents of the Westward travel surge. The injections are consistent with an Earthward pulse of electric field, modeled by Liu W. et al., (TGRL). The FAST satellite was passing underneath the THEMIS footprint at the time of onset. FAST observed field-aligned currents, ion outflows and electron precipitation consistent with the THEMIS observations of a Westward traveling surge in that region of space.

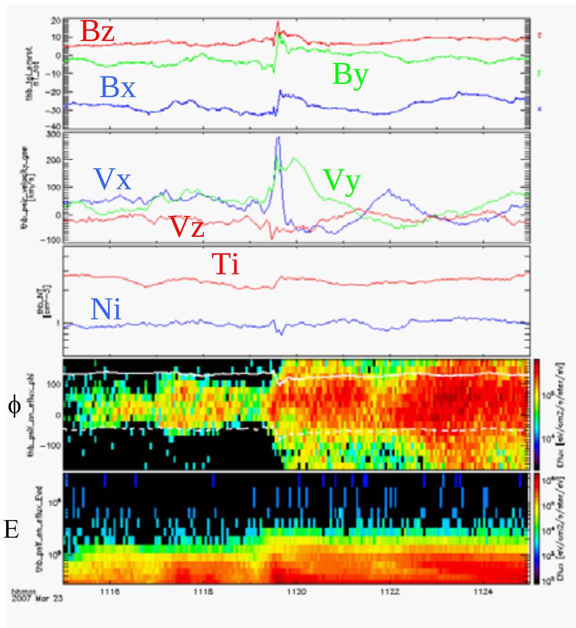

Figure 6A. A westward traveling surge in space (also see Figure 1). The earthward flow pulse (+Vx, second panel) at 1120 UT coincides with a bipolar (-,+) By magnetic field signature indicating a field-aligned current. Energetic particles moving duskward (ϕ = 90°) then dawnward (ϕ = -90°) arrive (4th panel) as fluxes increase at 1120 UT (5th panel). Remote sensing of the particle gyrocenters permits determination of the approaching hot boundary orientation and speed, which in turn provides information concerning the current's thickness and intensity (also see Figure 2B).

6.2 The birth of the storm-time ring current

THEMIS observes routinely not just the radiation belts but also the ring current and its source population during the course of substorms and storms. A handful of weak geomagnetic storms during the first 10 months of THEMIS allowed us to directly observe the inward motion of the plasma sheet, the freshly populated ring current and the persistence of the ring current after the retreat of the plasma sheet particles to larger distances.

Panels d to f of Figure 6B show profiles for PSD (Phase Space Density) multiplied by the magnetic moment μ as functions of μ and radial distance in the quiet period before, during, and after the main phase of the storm. The upper and lower dashed curves indicate the μ values corresponding to our definition of the ring current, namely ions and electrons with energies from 30 and 200 keV in the region between r = 2 and 7 R_E. Figure 6B demonstrates that the PSD of plasma sheet particles (μ ~1 to 10 keV/5 nT for ions and μ ~0.1 to 2 keV/5 nT for electrons) remains similar, from r ~13.7 R_E at the magnetopause to r ~6-8 R_E for ions and to r ~11.5-12 R_E for electrons, but then drops quickly further inward. Particles with lower μ penetrate further Earthward, consistent with energy-dependent separatrices between open and closed particle drift paths (the Alfvén layers), indicating that the drops represent the inner edges of the plasma sheet. Then the similar fluxes at the magnetopause and the inner edges indicate plasma sheet particles on open drift paths. During these pre-storm quiet times, the open drift paths do not extend to the ring current.

During the main phase, Figure 6B (e), the inner edges of the plasma sheet move earthward to ~3.5-4.5 R_E for ions and ~6-7 R_E for electrons. Now convection is stronger and the ring current ions can be supplied by open drift paths that extend further Earthward. The electron increase inside r = 6 R_E may be due to electrons having penetrated to r < 6 R_E earlier at the post-midnight local times, drifting eastward and suffering strong losses. During the late recovery phase, 6B (f), the inner edges of the ion and electron plasma sheets return to their pre-storm quiet time locations precluding supply to the ring current region. There is a clear separation between the plasma sheet ions on open drift paths and plasma sheet/ring current ions left behind on closed drift path region. The PSD in the ring current is lower than that during the main phase due to loss but higher than its pre-storm time value.

The above sequence demonstrates that the plasma sheet is the source of the majority of the ring current ions during geomagnetic storms. During the recovery phase, the open drift paths retreat tailward, leaving behind plasma sheet particles trapped in the ring current region on closed drift paths. In the absence of a particle source, losses cause a gradual decrease of ring current phase space densities to quiet time values.

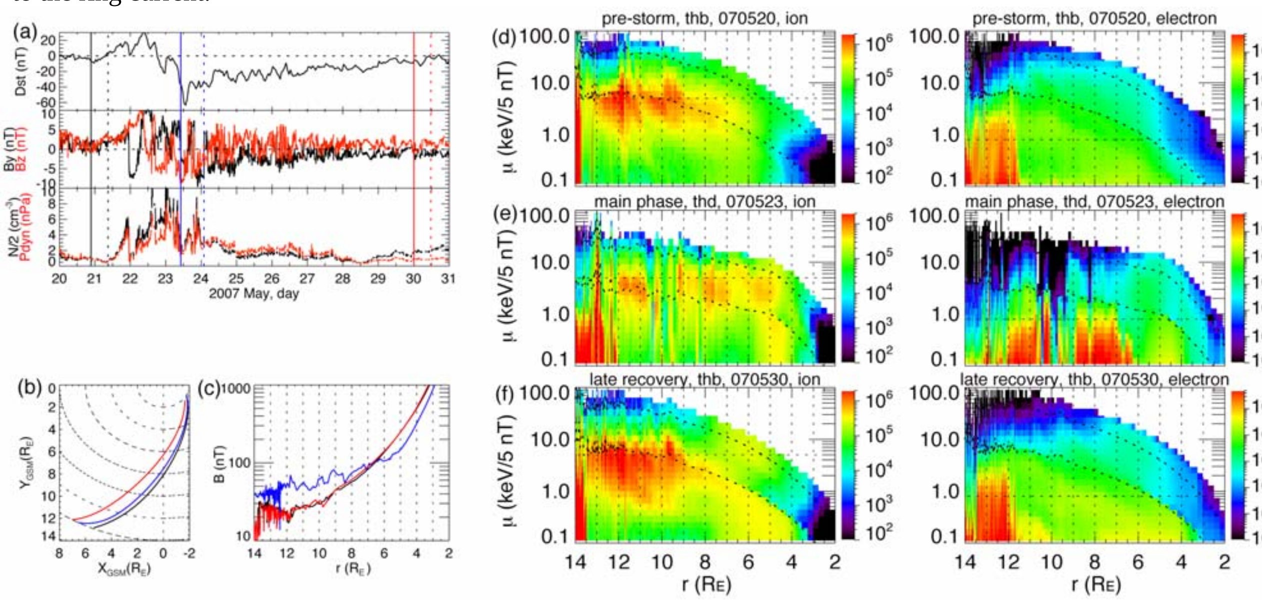

Figure 6B. (a) Dst, the IMF By and Bz, and solar wind density, and solar wind dynamic pressure measured by Wind (at X_{GSM}~ 236 R_E, Y_{GSM}~81 R_E, Z_{GSM} ~ 48 R_E) during the May 23, 2007 storm. The vertical lines indicate three inbound passes by TH-B and D during pre-storm (black); main phase (blue); and late recovery (red). (b) THEMIS orbits during the times of interest. (c) Magnetic field strengths as a function of radial distance. (d-f) Ion (left) and electron (right) phase space densities as function of radial distance for the three radial cuts of the inner magnetosphere. Plotted is $f \cdot \mu$ (in s^3km^{-6}) versus $\mu = E_k/B$, where E_k is the particle's kinetic energy, B is local magnetic field strength, and f is computed using omnidirectional fluxes). The lower and upper dashed curves indicate E_K = 30 and 200 keV, respectively.

6.3 A detached FTE at the magnetopause

A recent study addressing the internal structure of flux transfer events (FTEs) provides an excellent example of how multipoint THEMIS observations and high resolution numerical simulations can be combined to resolve longstanding questions [Sibeck et al., TGRL]. Transient reconnection along parallel dayside reconnection lines generates flux ropes of interconnected magnetosheath and magnetopheric magnetic field lines that bulge outward into both regions and move under the combined influence of pressure gradient and magnetic curvature forces. Because magnetosheath and magnetospheric magnetic field lines must drape over the flux ropes, their passage disturbs the surrounding media. FTEs marked by enhanced magnetic field strengths and bipolar magnetic field signatures normal to the nominal magnetopause, are common in the immediate vicinity of the magnetopause.

However, it has been argued that the same signatures can be produced by boundary waves driven by either the Kelvin-Helmholtz instability or solar wind/foreshock pressure pulses. Furthermore, some FTEs exhibit far more complicated, and as yet unexplained, signatures. Labelle et al., [1987] reported transient events with strong core magnetic field strengths bounded by deep troughs of weak magnetic field strength, bounded in turn by magnetic field strength enhancements. Despite detailed single-spacecraft studies [e.g., Farrugia et al., 1988], the absence of multi-spacecraft observations has precluded the development of a physics-based model for these 'crater' FTEs.

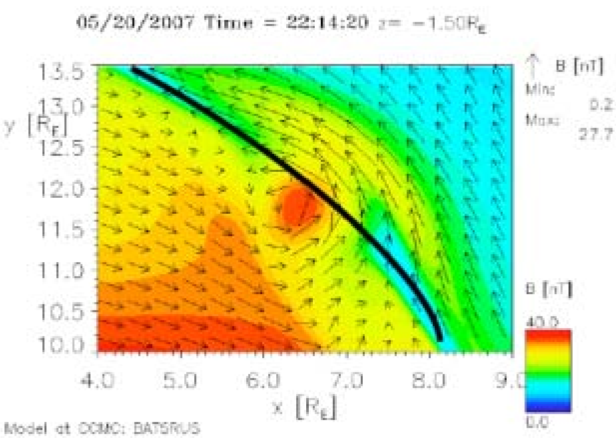

Figure 6C. Predictions of the BATS-R-US global MHD model with enhanced spatial resolution for the conditions prevailing at 2202 UT on May 20, 2007. An FTE with a strong core magnetic field moves duskward and antisunward through the magnetopause current layer. The solid black line marks the location of the magnetopause current layer.

Comparisons of multipoint THEMIS observations with the predictions of numerical simulations can aid in the interpretation of event signatures and in evaluating the significance of each mechanism. Figure 6C presents predictions of the BATS-R-US global MHD model with enhanced (0.16 R_E) spatial resolution for the conditions prevailing on the equatorial post-noon magnetopause at 2214:20 UT on May 20, 2007. The model predicts a detached island of enhanced magnetic field strengths greater than those in either the nearby magnetosheath or magnetosphere. The island bulges outward into both the magnetosheath and magnetosphere, causing modest magnetic field strength enhancements in both regions. Spacecraft that remain in the magnetosheath or magnetosphere should simply observe enhanced magnetic field strengths during the passage of the events. However, some spacecraft in the outer magnetosphere may pass through the weak magnetic fields of the current layer to enter the strong magnetic fields of the island and then return to the magnetosphere. The latter spacecraft should observe crater FTEs with weak magnetic field strength troughs bounding strong core field strengths. As illustrated by the magnetic field lines spiralling about the island in figure 6C, all the spacecraft should observe bipolar magnetic field signatures normal to the nominal magnetopause during the event.

Figure 6D [Sibeck et al., TGRL] presents THEMIS magnetic field observations from 2200:30 to 2203:30 UT on May 20, 2007 in boundary normal coordinates. THEMIS-B and –C were in the post-noon equatorial magnetosphere, observing northward (B_L>0) fields. TH-E and –A were in the post-noon magnetosheath observing variable southward and duskward (B_M<0) components. TH-D was in between the others in the magnetopause current layer, where the L-component of the magnetic field varied between magnetosheath and magnetospheric values. Thus the constellation bounded the magnetopause, with TH-B (nearest Earth) and –A (furthest from Earth) separated by 0.65 R_E in radial distance.

The THEMIS observations in Figure 6D are consistent with the predictions of the model shown in Figure 6C. TH-D, in the current layer, observed the largest magnetic field strength enhancement within the core region of the event. All of the spacecraft observed (-, +) bipolar magnetic field signatures centered on 2202 UT, indicating an event that simultaneously bulges outward into both the magnetosheath and magnetosphere. TH-B and –C observed the crater-like magnetic field strength structures with a strong core field, deep troughs, and bounding magnetic field strength enhancements predicted for spacecraft that exit the magnetosphere and transit the current layer to enter the strong core magnetic fields within the FTE. The successful comparison provides striking evidence for the power of combined simulation results and multipoint observations.

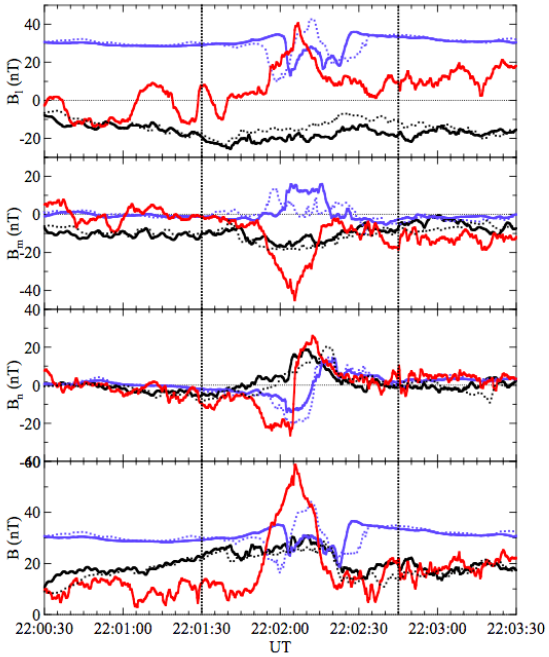

Figure 6D. THEMIS encounter with an FTE on May 20, 2007. TH-A (black solid), -B (blue solid), -C (blue dashed), -D (red), and –E (black dashed) observations, in LMN, or boundary normal, coordinates: L is along the magnetospheric field, N is normal to the magnetopause and M completes the right-handed triad.

6.4 Hot Flow Anomalies

Hot Flow Anomalies (HFAs) are kinetic phenomena that occur when certain IMF tangential discontinuities intersect the bow shock [e.g. Schwartz et al., 2000]. The solar wind convection electric field must point into the discontinuity on at least one side and the magnetic field must connect to the oblique, or quasi-parallel shock on at least one side (see Figure 6E). The process by which HFAs form, the relationship between their signatures upstream and downstream from the bow shock, and the mechanisms by which incident and reflected ions and electrons are heated to form single populations within the events remain unclear.

THEMIS offers numerous opportunities for simultaneous observations of HFAs upstream and downstream from the bow shock. On 4 July 2007, the THEMIS probes encountered an HFA on the dusk side of the Earth's bow shock, near the point where an abrupt IMF discontinuity first encountered the bow shock [Eastwood et al., 2007, TGRL]. THEMIS-A, upstream from the bow shock in the solar wind, observed the classic HFA signatures shown in Figure 6E: a heated core region with strong flow deflections bounded by correlated density and magnetic field strength enhancements. The other THEMIS probes were located in the magnetosheath, where THEMIS-E (closest to the bow shock) observed flow disturbances, THEMIS-C and -D saw waves, and THEMIS-B (furthest from the bow shock) recorded only large fluctuations in the field strength. These observations suggest that the THEMIS constellation observed a nascent HFA. Subsequent to its observation by the THEMIS probes, the HFA launched a pressure pulse that swept westward across the dayside magnetopause, generating auroral brightenings, field-aligned currents, and corresponding ground magnetometer signatures. Ongoing studies include a reconstruction of the corresponding magnetic impulse event vortex from these northern hemispheric and Antarctic ground magnetometer observations and images. Forthcoming surveys will test the hypothesis that older HFAs contain single hot ion distributions, extend further from the bow shock into the magnetosheath, and exhibit stronger perturbations in the upstream region later in their lifetime.

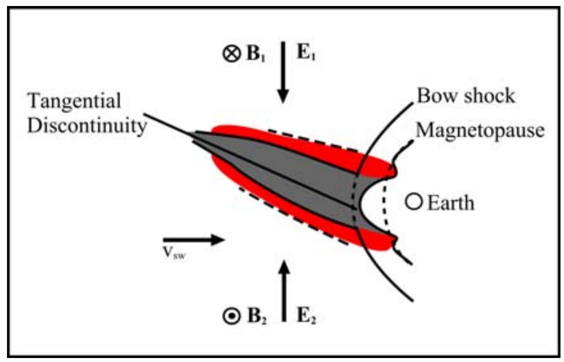

Figure 6E. Artist's conception of an HFA at the Earth's bow shock. In absence of simultaneous multipoint measurements, the internal structure and relationship between between features upstream and downstream from the bow shock remain unclear.

6.5 Other discoveries to date

The THEMIS team took advantage of the string-of-pearls spacecraft configuration during the coast phase of the mission not only for instrument commissioning and inter-calibration but also to conduct unique science. This section summarizes some of the main discoveries of the coast phase. More than 30 publications have been submitted in special issue of GRL. Others have been submitted in Space Science Reviews, and more are being submitted in a special issue of JGR. THEMIS publications can be found at: http://themis.ssl.berkeley.edu/publications.shtml

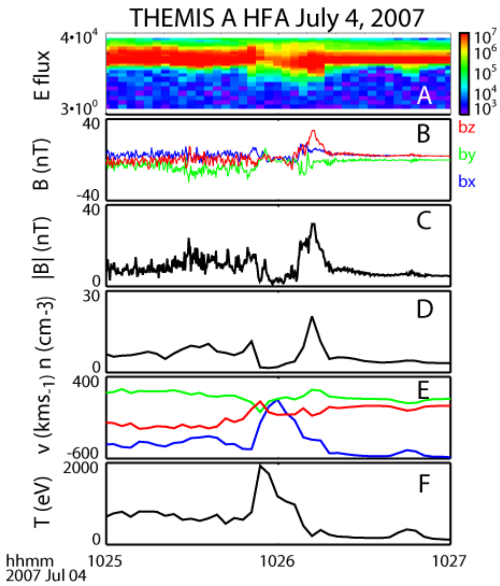

Figure 6F. An HFA observed by THEMIS-A on July 4, 2004. From top to bottom, panels in the figure shows the ion distribution function, magnetic field components, magnetic field strength, density, velocity components, and temperature.

6.5.1 Magnetotail

- **Identified drivers of storm time flapping.** THEMIS's multi-probe observations show that fast flows in the magnetotail drive plasma sheet waves that flap north-south. With several R_E amplitudes as large as the plasma sheet thickness, these waves were seen for the first time during storms. The waves provide clues concerning the dynamic stability of the current sheet and the means by which energy in the tail is dissipated. (Gabrielse et al., TGRL)
- **Observed and modeled dynamic evolution of near-Earth tail and waves.** While in the string-of-pearls configuration, THEMIS observed the first evidence of rapid (1-2 hr) inward and outward motion of the near-Earth tail in response to substorm electric fields (Runov et al., TGRL; Liu W. et al., TGRL).
- **Substorms are a multi-step processes.** Global imaging and careful mapping of ground array data and string-of-pearls spacecraft observations provide the first evidence that most substorms occur in sequence of steps: a small precursor, a poleward-moving main onset, and a dominant intensification [Mende et al., 2007].
- **First signature of ground onset identified.** Careful onset timing points towards waves with 12-40s periods, "Pi1", as the first marker of substorm onset. These are observed eastward of the substorm meridian, telling us how the ionospheric conductivity affects a substorm's evolution (Milling et al., TGRL).
- **From solar wind shock to substorm onset.** THEMIS's string-of-pearls observations and ground array, coupled with those by a dozen other ancillary spacecraft, performed the first comprehensive observations and modeling of a solar wind shock propagating through the magnetosphere and triggering substorm onset (Keika et al., TJGR).
- **Ballooning aurorae seen in space.** The THEMIS ground arrays observed the first clear evidence of ballooning modes occurring in the near-Earth tail and participating in substorm evolution while the THEMIS probes corroborated outward plasma motion. (Voronkov et al., TGRL; Connors et al., TGRL).

6.5.2 Inner Magnetosphere:

- **Plasmaspheric plumes feeding reconnection.** THEMIS's string-of-pearls formation distinguished spatial from temporal variations of structured plasmaspheric plumes; they were found to be adjacent to the magnetopause where they form a layer of cold ions partaking in magnetopause reconnection (McFadden et al., TGRL).

6.5.3 Dayside:

- **Turbulent heating at the magnetopause.** Comprehensive instrumentation and multi-point observations resolved the k-spectrum of waves at the magnetopause, and identified kinetic Alfvén waves as the mode of magnetopause turbulence. Diffusion coefficients suffice to account for the transport of magnetosheath plasma across the magnetopause (Chaston et al., TGRL).
- **First observations of asymmetric reconnection.** Due to large density and magnetic field strength jumps, magnetopause reconnection is generally asymmetric. Mozer et al. [TGRL] used the string-of-pearls configuration to show that the locations of the current density and "Hall" electric fields are consistent with theoretical expectations.
- **Discovery of the remote signatures of FTEs.** Theory predicts that FTEs perturb the ambient magnetosphere/sheath plasma and magnetic field as they move along the magnetopause. Simultaneous multipoint THEMIS measurements described these perturbations at various locations inside and outside FTEs, demonstrating that they were similar to those for plasmoids in the magnetotail (Liu et al., TGRL).

7. Technical/Budget

7.1 Technical

7.1.1 Observatory and instrument status As of this writing, the entire THEMIS constellation is in place and performing nominally. Automated operations support routine passes. Probe and instrument status is updated in real-time during pass-supports. The last recorded status is seen at: **http://soleil.ssl.berkeley.edu/ground_systems/themis_constellation_status.html**. Three instruments suffer from minor contamination effects. As anticipated, sunlight affects two sectors per spin of the SST. Spin harmonics and 32 Hz noise affect the SCM. An 11 Hz tone affects FGM. Post-processing software eliminates the first two problems, while the low amplitude (30 pT peak-to-peak) of the third makes it inconsequential for our science objectives. None of these problems affects data analysis. Instruments operate in Slow Survey (SS) mode most of the orbit, and in Fast Survey (FS) mode during conjunctions (~12 hrs/orbit). Those can be seen as horizontal bars in overview plots at: **http://themis.ssl.berkeley.edu/summary.php** Particle or low frequency field events (e.g. north/south magnetic field turnings in the magnetotail) trigger 8-12 min Particle Bursts (PB), while high frequency wave power events trigger 3-6s Wave Bursts (WB).

7.1.2 Status of ground systems All data processing and software continue to function reliably. All flight dynamics systems are nominal. Mission design runs with the latest orbit solutions are repeated regularly, covering the entire mission life to reaffirm conjunctions, shadows and fuel budget. Product generation, based on updated ephemeredes, is fully automated. GSFC flight dynamics provided backup orbit solutions for each probe once per month and more frequently during the orbit placement phase. Telemetry files are transferred post-pass from the ground stations to UCB are checked and archived. Level 0, 1 and 2 data processing is automated. Instrument scientists ("tohbans") review survey plots within ~1 day after receipt of data on the ground. See: at: http://sprg.ssl.berkeley.edu/~themistohban/ for tohban functions. The Berkeley ground station continues to function well. NASA Ground Network stations continue to support THEMIS nominally, while Universal Space Net has been certified and has started to support THEMIS. The NTR T-1 line from GSFC to the MOC over the Open IONet and 3 voice loops at the MOC continue to function nominally.

7.1.3 Prime mission to date (FY07/08). From launch until now, the five THEMIS probes underwent a combined 176 thrust operations. Instruments were turned on and commissioned, while magnetometer (2) and EFI booms (6) deployed flawlessly on all probes. Instrument parameters (ESA plate voltages, SST bias voltages, EFI bias current) were configured nominally, and undergo routine periodic tests.

7.1.4 Prime mission to end-of-prime (FY08/09). Following the 1^{st} tail season, a number of maneuver "tweaks" are needed to adjust the three inner probe orbits and keep them fixed in sidereal orbits. A large inclination change maneuver planned for P1 and P2 in the late summer of 2008 will counteract lunar perturbations of the orbit planes in time for the 2^{nd} tail season. We will conduct significant maneuvers to increase P5's orbital period, resulting in conjunctions with the other probes each 8, 4, and then 8 days, in the forthcoming 1^{st} dayside, 2^{nd} tail, and 2^{nd} dayside seasons, respectively. A total of ~50 nominal maneuvers are expected in the next 1.5 years. Depending on 1^{st} year results, a small number (3-5) of additional orbital adjustments for enhanced science (e.g. to ensure prolonged neutral sheet encounters for P1 and P2) may be needed.

7.1.5 Extended THEMIS Baseline (In-Guide)

Plans for P3,4,5. The extended THEMIS baseline plans call for modifying the P3,4,5 orbits to achieve 200 km to 1 R_E separations during the 3^{rd}, 4^{th}, and 5^{th} years of THEMIS operations in the Tail and Dayside. A string-of-pearls configuration, with separations similar to those during the coast phase, i.e. from 100 km to 2 R_E, is planned for inner magnetosphere studies, in the dawn and dusk sectors of the orbits. The required side-thrust maneuvers are of the same type, size, and duration as minor orbit change or tweak maneuvers of the prime phase. Sufficient fuel margin (>9%) remains on all probes at the end of the proposed extension, even when accounting for de-orbit fuel.

Fate of P1 if ARTEMIS is not selected. By the 3^{rd} year of THEMIS in-guide operations, P1's line of apsides will lie 54^o away from those of P3,4,5. This reduces the scientific usefulness of P1 in the context of the constellation. In addition, P1 will encounter 6.4 hr shadows. No expenditure of fuel can reduce shadows below the 3 hr battery design limit or the 45-hr battery drain limit. We expect P1 to become inoperable in its current orbit due to long shadows in March of 2010. The in-guide extended baseline calls for expending the P1 fuel and monitoring its status until its demise.

Plans for P2 if ARTEMIS is not selected. The line of apsides of P2 will also lie far (27^o) from those of P3,4,5 during the 3^{rd} year of operations. However, the shadows encountered in the nominal orbit (4.7hrs) can be minimized to 3.5hrs by reducing P2's apogee to 12 R_E (orbital period ~ 1 sideral day) in the Fall of 2009. The expected shadows fall within the battery capacity of P2 at the end of the prime mission. P2 is thus expected to survive, albeit in an In-Guide orbit where it can provide only contextual observations for the baseline mission. Routine (mostly automated) operations for P2 in its sidereal orbit thereafter are absorbed in the proposed In-Guide budget, and insignificant relative to the proposed baseline operations of P3,4,5.

Instrument operations. Modes and data relays will proceed as during the prime mission, with 12 hrs of FS and 1.2hrs total of PB per orbit. However, new "inner magnetospheric" bursts, triggered by enhanced fluxes of energetic particles will address new inner magnetosphere goals of the extended mission. Nominal instrument operations are assumed in the In-Guide plan, but savings from automation and familiarity of the team with instrument operations will reduce mission and science operations personnel.

7.1.6 Optimal Extended THEMIS Baseline Over-Guide. (a.k.a. THEMIS Low) This plan assumes that ARTEMIS is selected and P1 and P2 begin their ascent towards the moon in late 2009. The technical plan is almost identical in scope to the In-Guide plan; the only exception is that preparations for P1's demise and P2's salvage into a sidereal period orbit do not have to be performed. The operational savings from those two items is insignificant, since minimal resources are required to operate the inner three-probe constellation and since P2's operations are largely automated.

7.1.7 ARTEMIS: The mission design and operations plan for ARTEMIS calls for raising the apogees of P1 and P2 and using lunar and Earth flybys to insert the probes into weakly stable orbits at the two Earth-Moon Lagrange points, LL1 and LL2, approximately one year after the initial Earth-departure operations, i.e., at the start of FY11. After a 5-month residence at the Lagrange points, the probes are inserted into stable, 24hr period equatorial lunar orbits, for ~17 months of operations, i.e. until the end of FY12. Science optimization of this orbit sequence has taken place since April 2005 in consultation with the same JPL group that validated the THEMIS mission design.

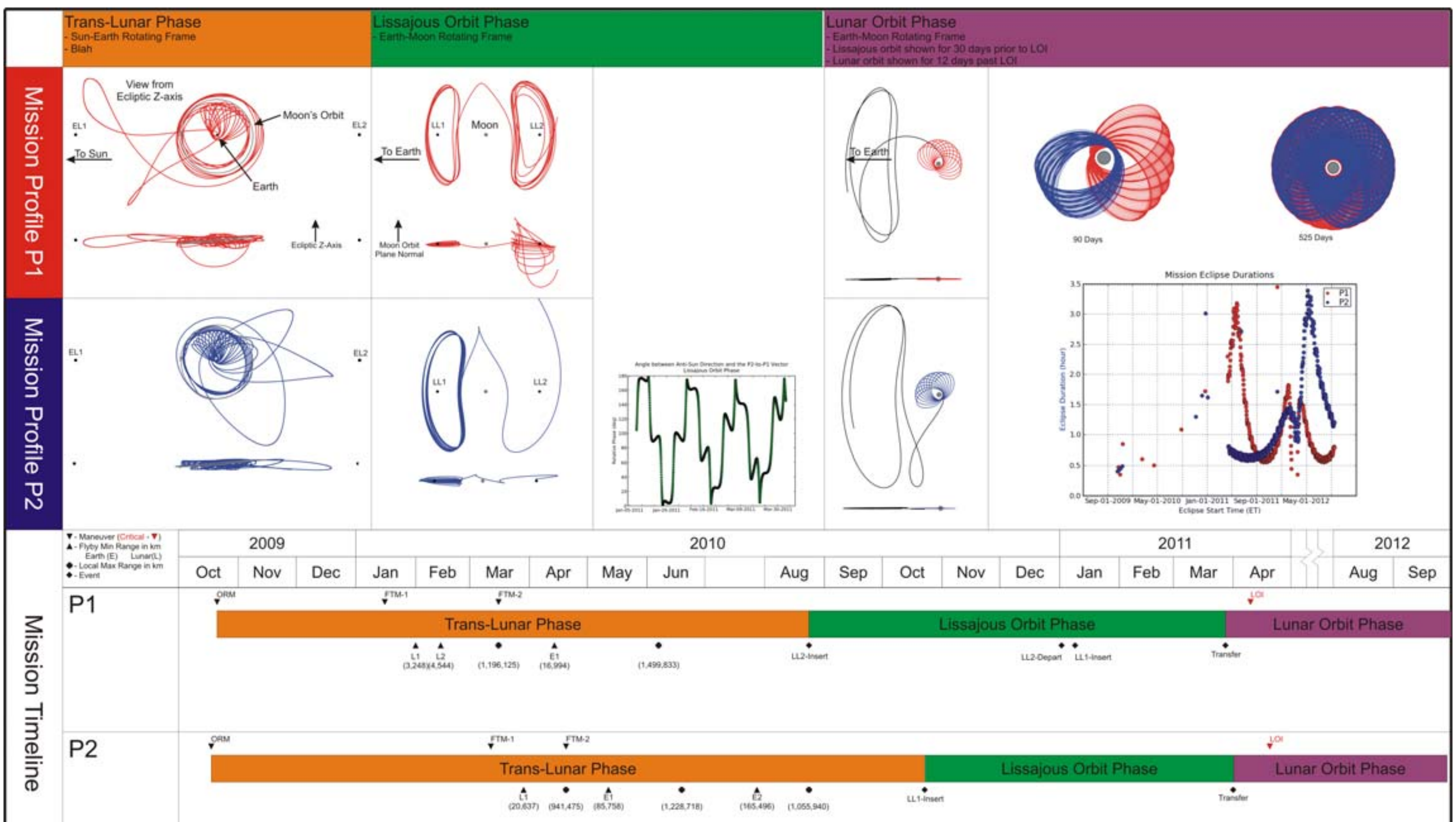

Figure 7A. Overview of mission profile for ARTEMIS

At the Lagrange points the probes execute Lissajous orbits with ~14 day periods. The Lissajous orbit phase design has a dual goal: operationally, it prepares the team for accurate, low risk orbit insertions, while orbit evolution flattens the orbit of P2 after previous out-of- (ecliptic) plane motion (Figure 7A). Scientifically, this phase results in a range of large inter-probe separation distances (10-20 R_E) and

Sun-angles suitable for studies of large-scale phenomena in the magnetotail, solar wind, and lunar wake. There are two Lissajous orbit sub-phases. From late October 2010 to early January 2011 the probes are on opposite sides of the moon; from January 2011 to early April 2011 the probes are on the same side.

The equatorial lunar orbit design simultaneously optimizes science return and reduces mission operations complexity: P1 is retrograde and P2 is pro-grade, resulting in fast relative precession of the line of apsides. The orbits precess a full 360^o relative to each-other in the proposed 17-month long lunar orbit phase, which provides for a wide range of inter-probe separations and longitudes as needed for the science objectives. The easier to achieve, retrograde orbit is reserved for P1 to increase its margin; the fast relative precession of P1 and P2 removes the inertial longitude of insertion from the design requirements.

A JPL internal review on Nov 2, 2007 found no technical issues with the proposed design and recommended further work on navigation error estimates. The GSFC/FDAB team was integrated into the proposed team on Dec 4^{th}, 2007 to provide experience in Lunar phase Navigation, trajectory correction maneuvers, and maneuver design, as well as experience with the THEMIS operations tools from the THEMIS-prime mission. Since then, the team minimized maintenance fuel (shown in Table 7A) and fine-tuned the DSN contact schedule. A peer review at GSFC on Feb. 12, 2008, strengthened the proposed plan and re-asserted our confidence that the team can achieve the goals proposed in the time allotted.

The ARTEMIS mission design is optimized to maximize science and reduce risk. It satisfies the science goals of the mission and has already undergone several technical reviews. The design team is composed of the world's leading experts in translunar injection, weak stability points, and lunar orbit insertion and already has several years of familiarity with the THEMIS probe capabilities.

The ARTEMIS probes will operate in the standard SS, FS, PB and WB modes. To accommodate the lower data returns expected from lunar distances, FS will be curtailed by factor of 4 and there will only be two PB per orbit, either time- or trigger-based. Time-based burst selection will occur by science operations meetings in an observatory manner. WBs will be obtained within PBs using standard wave triggers. This results in a total volume of 200 MB of compressed data / 2 days.

ARTEMIS proposes to use the DSN 34m BWG antennas for communications at 3.5 hrs/probe/2 days. The proposed DSN pass duration allows 0.5hr of use of a range channel for orbit determination purposes, followed by a transition into a 3hr-long, science telemetry recovery mode. At a maximum lunar range of 64 R_E with the known G/T of the DSN 34m BWG stations, we obtain:

- DSN, science: 65.536 kbps / 3.2 dB margin
- DSN, ranging: 16.384 kbps / 2.1 dB margin

Assuming 32kbps represents a worse case scenario for reasonable lunar orbit view-angles (~5^o to ecliptic), and spin-axis tilts planed for science operations (~8^o to ecliptic), we observe that we can collect ~337.5 Mbits / 3 hr contact. This exceeds mission requirements by more than a 50% margin.

7.1.8 ARTEMIS Mission Development plan. The ARTEMIS science and mission implementation teams (UCB, JPL, GSFC and UCLA) are holding weekly telecons and face-to-face meetings to further solidify the mission design. A detailed development schedule has been developed and was peer reviewed. Maneuver independent validation, navigation error characterization, trajectory correction maneuver (TCM) implementation, and operations training are scheduled for the period July '08 to Oct. '09.

ARTEMIS Mission (P1, P2): ΔV overview				
Phase	Interval	Maneuvers	dV P1	dV P2
TLI	Oct.09-Oct.10	Orbit raise, Lunar fly-by	100.7	185.6
		Declination, Gravity Losses	20	28
LL1,2	Oct.10-Jan.11	DSM	0.9	17.3
LL1	Jan.11-	Maintenance	15	12
LO	Apr.11-Sep.12	Lunar transfer initiation, LOI	86.6	108.7
		Decl., Gravity, Steering	7	12
all	all	TCMs	13	10
Total required for this ARTEMIS probe:			243	374
Total available at end of prime mission:			300	450
ΔV available ARTEMIS margin [m/s]			**57**	**76**
ΔV available for ARTEMIS margin (%)			**23%**	**20%**

Table 7A. Most operations on P1, P2 have been completed. Remaining prime mission THEMIS maneuvers are few, deterministic and low risk. End-of-mission fuel, available for ARTEMIS, is therefore quite secure and sufficient to perform the mission.

8. Public Affairs

Our vigorous public affairs program at NASA/GSFC achieved remarkable successes during the past year. The THEMIS launch was covered extensively by the media and the launch video was advertised by www.nasawatch.com and received more than 21,000 hits on "YouTube". The Fall 2007 AGU new results press conference was well attended and was well covered by the print media. It resulted in numerous interviews broadcast by BBC, CBC, and NPR, including a feature on the NPR program Earth & Sky. We gave presentations at the Maryland Science Center, will be returning there in 2008, and doing the same at the Smithsonian. PBS's Newshour presented a special report on our E/PO efforts to engage Alaskan students and is preparing a follow-up program.

9. Education and Public Outreach

Fig. 9A. Blue does indicate the locations of schools with magnetometers, red dots indicate science observatories.

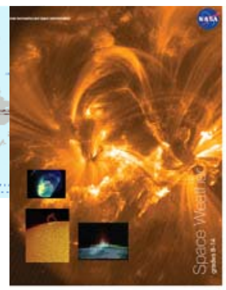

Fig. 9B. An example of a THEMIS teacher's guide that will be used in the future programs.

The main goal of our E/PO program is to help inspire rural and Native American high school students to become engaged in Earth, space and physical science. Figure 9A illustrates the locations of each of the 12 schools in 10 US states that hosts one of our research-grade magnetometers and participates in our E/PO program. We hold yearly workshops for the teachers, make the magnetometer data available on the web in real-time, and develop, test, and revise teacher guides (see Figure 9B). We actively maintain a WWW site (http://ds9.ssl.berkeley.edu/themis/) that provides comprehensive and updated information for the general public, students, and teachers as well as evaluation results from our programs.

THEMIS is equally interested in higher education. Table 9A is a breakdown of the 47 young scientists (24 in the US) supported by the project.

Country	Under grads	Grads	Post-docs	Research Associates
Austria		1	1	
Canada	1	7	4	3
Germany		1	2	
Russia	1	2		
USA	3	9	11	1

Table 9A. *Young scientists supported on THEMIS.*

We will propose to expand the GEONS program to broaden its content by collaborating with other E/PO partners and also address an African American audience. We will train educators to become "Heliophysics Ambassadors" of the THEMIS and ARTEMIS missions (in tandem with FAST, AIM, and RHESSI). As part of this program we will teach about space currents which drive the aurora, and are a result of the space environment effects on our planet. Using THEMIS, STEREO, ACE, RHESSI, and FAST data we will help educators teach the Sun-Earth cause-and-effect relationship in the growing activity period towards solar max. ARTEMIS content will include space hazards for astronauts on their way to the moon, and how the radiation environment affects future exploration of Mars. We will support updates to the Sun-Earth Viewer, together with the Sun-Earth Education Forum and ACE, Ulysses, and Voyager.

10. References

Publications which appear in a special issue on THEMIS are referenced in the text as TSSR, TGRL, TJGR (THEMIS-SSR, -GRL or –JGR). These are at:
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11. Acronyms

ACE Advanced Composition Explorer
AGU American Geophysical Union
ALSEP Apollo Lunar Surface Experiments Package
ARTEMIS Acceleration, Reconnection and Turbulence, and Electrodynamic of Moon's Interaction with the Sun
ASI All Sky Imagers
BATS-R-US Block Adaptive-Tree Solar-wind Roe-type Upwind Scheme. also: http://www.cscamm.umd.edu/cmpd/michigan.htm
BBC British Broadcasting Corporation
BBF Bursty Bulk Flow
BWG Beam Wave Guide
CBC Canadian Broadcasting Corporation
CMI Coronal Mass Ejection
CNN Cable News Network
CRATER Cosmic Ray Telescope for the Effects of Radiation
DARTS Data Archives and Transmission System http://darts.isas.jaxa.jp/stp/ http://darts.isas.jaxa.jp/stp/cef/themis/themis.cgi
DC Direct Current
DoE Department of Energy
Dst Disturbance, Storm Time
EFI Electric Field Instrument
EMIC Electromagnetic Ion Cyclotron
E/PO Education and Public Outreach
ESA Electrostatic Analyzer
FAC Field-Aligned Current
FAST Fast Auroral Snapshot Explorer
FGM Fluxgate magnetometer
FTE Flux Transfer Event
FY Fiscal Year
GBO Ground-Based Observatories
GEM Geospace Environment Modeling
GEONS Geomagnetic Event Observation Network by Students
GEOS Geostationary Scientifc Satellite
GI Guest Investigator
GMAGS Ground-Based Fluxgate Magnetometers
GOES Geostationary Operational Environmental Satellites
GPS Global Positioning System
GRL Geophysical research Letters
GSE Geocentric Solar Ecliptic
GSFC Goddard Space Flight Center
GSM Geocentric Solar Magnetospheric
HF High frequency
HF Hot Flow Anomaly
HP Heliophysics
HQ Headquarters
IMF Interplanetary Magnetic Field
JGR Journal of Geophysical Research
KeV Kiloelectron Volt
LANL Los Alamos National Laboratory
LL1 Lunar Libration 1 point (between Earth and Moon)
LL2 Lunar Libration 2 point (Along Earth-Moon on other side of moon)
LP Lunar Prospector
LRO Lunar Reconnaisance Orbiter
MAP Mission Data Archive Plan
MeV Mega electron volt
MFTR Magnetic field transition region
MHD Magnetohydrodynamics
MHz MilliHertz
MOC mission operations center
MSNBC Microsoft Network- National Broadcasting Corporation
NAC NASA Advisory Council
NASA National Aeronautics and Space Administration
NOAA National Oceanic and Atmospheric Administration
NPR National Public Radio
NRC National Research Council
NSF National Science Foundation
P1,2,3,4,5 THEMIS Probes 1,2,3,4,5 corresponding to letters B, C, D, E, A
PBS Public Broadcasting System
Pc 1 Continuous pulsations, period 0.2 to 10s
PSD Phase Space Density
R_E Earth Radius
R_L Lunar Radii
Rx Reconnection
SAMPEX Solar Anomalous and Magnetospheric Particle Explorer
SAPS Subauroral polarization stream
SCM Search Coil Magnetometer
SDO Solar Dynamics Observer
SED Storm-enhanced plasma density
SELENE SELenological and ENgineering Explorer
SIDE Suprathermal Ion Detector Experiment, part of ALSEP
SMPD Small Plasma Device
SOC Science Operations Center
SOHO Solar and Heliospheric Observatory
SPDF Space Physics Data Facility
SSE Selenocentric Solar Ecliptic
SSR Space Science Reviews
SST Solid State Telescopes
STEREO Solar Terrestrial Relations Observatory
SuperDARN Super Dual Auroral Radar Network
SW Solar Wind
TC-2 Polar Orbiting spacecraft of the Chinese Double Star program
THEMIS Time History of Events and Macroscale Interactions

TGRL	THEMIS special issue of Geophysical Research Letters, submissions closed Feb 15, 2008. See papers at:http://themis.ssl.berkeley.edu/publications.shtml
TJGR	THEMIS special issue of Journal of Geophysical Research, submissions will close on April 30, 2008. See papers at:http://themis.ssl.berkeley.edu/publications.shtml
TSSR	THEMIS special issue of Space Science Reviews, submissions will close on April 30, 2008. See papers at:http://themis.ssl.berkeley.edu/publications.shtml
TIMED	Thermosphere-Ionosphere Mesosphere Energetics and Dynamics
TLI	Trans-Lunar Injection
UCB	University of California at Berkeley
UCLA	University of California at Los Angeles
ULF	Ultra low frequency
USA	United States of America
VLF	Very low frequency
WWW	World Wide Web

X-line reconnection line

ω_{ci} Ion Cyclotron Frequency (Gyrofrequency)

ω_{pi}, Ion Plasma Frequency