TIME HISTORY OF EVENTS AND MACROScales Interactions during SUBSTORMS: THEMIS

PROPOSAL SUBMITTED FOR:

SENIOR REVIEW 2010 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM

FOR THE

HELIOPHYSICS OPERATING MISSIONS

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1. Executive Summary

THEMIS, a five satellite (a.k.a probe) constellation mission, was launched on February 17, 2007. After instrument commissioning and inter-calibration (“coast phase”) science at the dayside magnetopause, THEMIS entered science orbits on December 4, 2007. Baseline observations commenced after the “spare satellite” P5’s EFI instrument deployment on January 11th, 2008. In the 2 years since, the THEMIS constellation and its 20 Ground Based Observatories (GBOs) have returned groundbreaking data from an unprecedented set of Sun-Earth aligned configurations.

With hundreds of substorm observations at hand, and at least two dozen of those from the unique vantage point of tail-alignments, THEMIS has been able to reach closure on its prime science objectives and redefine the course of substorm research. While the trigger mechanism of onset has been identified as magnetic reconnection (Rx), the interaction of the Rx outflow with the inner magnetosphere is far more complex than previously thought: Ion-gyroradius-scale, plasma-depleted flux tubes emanate from the Rx site. Over a 10-20Re distance these tubes propel and churn the plasma sheet. Kinetic phenomena at their edge and inside them drive wave instabilities, particle scattering and energy dissipation; while the collective interaction of multiple dipolarization fronts at the near-Earth plasma sheet is responsible for global substorm expansion (possibly due to a separate plasma instability there). These plasma injections not only feed the ring current and radiation belts, but also provide the conditions needed for the growth of chorus, electromagnetic ion cyclotron (EMIC), and electrostatic cyclotron harmonic (ECH) waves, all of which play crucial roles in driving storm processes. On the dayside, magnetopause transients have been shown to cause enormous magnetospheric undulations and to drive ULF pulsations which, in turn, also effect radiation belt dynamics. THEMIS studies on these topics have opened new directions for the understanding of energy coupling between freshly injected particles, radiation belt populations, and the ionosphere through wave-particle interactions.

From FY11-14, THEMIS will continue to lead the substorm community by tracking the flow of energy from the mid-tail reconnection site to the inner magnetosphere. The approach will be two-staged: In FY11/12 the inner three probes will be placed in clustered (tail/dayside) or “string-of-pears” (dawn-dusk) orbits at smaller scales than ever before attained in the equatorial near-Earth magnetosphere inside of 12Re (Table 1A). When in clustered separations from 1Re down to ion gyroradii (~100km), probes P3,4 & 5 will address the nature, evolution, and interaction of dipolarization fronts, the structure and evolution of the near-Earth current sheet, wave-growth and propagation during injections, and how kinetic processes at the inner edge of the plasma sheet affect the global substorm instability.

At the dayside, from their clustered vantage-points at the subsolar magnetopause, THEMIS probes P3,4 and 5 will be ideally positioned to resolve questions regarding the physics of asymmetric reconnection and the response of the boundary to external drivers using separations along the XYGSE plane, at 100s to 1000s of km unique for the equatorial magnetosphere.

In the dawn-dusk sector and from its “string-of-pears” orbits at 500km – 3000 km distances, THEMIS will explore generation of chorus, hiss, EMIC and ECH waves and large amplitude whistler mode electric fields by injected, drifting particles. The orbits will also be ideal for separating spatial from temporal effects and the effect of waves and large electric fields on particle acceleration or loss, a question central to radiation belt physics. Thus, in FY11/12 THEMIS will also lay the groundwork for the upcoming launch of the RBSP and MMS missions.

Building upon the expected knowledge gained from its upcoming Cluster-like, 2 year “microphysics” phase, the THEMIS team proposes to expand the constellation scale-size again in FY13/14, in order to investigate sources and sinks of energy and transport of particles on a global scale: i.e., from the nightside plasma sheet or the dayside magnetopause into the inner magnetosphere. Synthesizing knowledge gained from its previous two phases and using its full complement of particles and fields instruments THEMIS will address questions related to cross-scale coupling. With along-track separations of 4-8-12hrs, (or 8-8-8 hrs) on their 24 hour period,12Re apogee orbits, one THEMIS probe will always guaranteed to be at L>10 while one or two other probes will simultaneously be measuring phase space densities on inner magnetospheric L-shells for comparison with observations of sources and sinks further out. Surpluses or deficiencies from adiabatic convection can thus be attributed to local acceleration or losses, and the wave measurements needed to confirm the attribution will be readily available. The key questions to be addressed in this period are not unique to THEMIS but lie at the heart of a concerted effort by NASA (RBSP, BARREL) and international partners (Orbitals, ERG) to understand the radiation belts during the upcoming solar maximum.

THEMIS will make seminal contributions to these international efforts, by providing unique and crucial observations of: (i) the high L-shell source population for the radiation belts (ii) the magnetopause boundary processes that drive the magnetosphere, and (iii) particles and fields at 2 additional locations inside of L=10. In particular THEMIS will also provide accurate observations of the Sun-Earth directed component of the electric field that will be less-well determined by RBSP’a axial booms. Database and analysis tool exchanges with those missions have already begun, in anticipation of what promises to be a golden era for inner magnetospheric research.

To optimize the science yield from its outermost two probes and evade detrimental long shadows in March 2010, a community of scientists working with a subset of
the THEMIS team proposed to send THEMIS probes P1 & P2 into stable, lunar equatorial orbits, where they will form the new mission called ARTEMIS (Figure 1A). The Heliophysics and Planetary divisions requested and are currently evaluating a separate ARTEMIS proposal. If accepted, ARTEMIS probes P1 and P2 will begin making the first systematic, two-point solar wind and distant magnetotail observations with comprehensive instrumentatio at separations ranging from 100s of km to 20RE in October 2010. THEMIS plans to make full use of these two-point solar wind measurements when the moon is in the solar wind, because P1 and P2 will be ideally positioned directly upstream from Earth’s bow shock.

The health of the constellation is excellent: there has been no measurable degradation of battery charge capacity, or electronics from radiation or thermal cycling. Team productivity, as evidenced by >135 accepted refereed publications (see: http://themis.ssl.berkeley.edu/publications.shtml), and >95 presentations at the recent AGU meeting is healthy and accelerating. Of those, >40% are led by scientists not affiliated directly with the co-I team or funded by THEMIS, and >40% are by young researchers. THEMIS’s results were featured as: one of the “Top Ten Stories of 2008” in Astronomy magazine; “CNN’s most popular science story”; Cover stories in 3 journal issues (Science, GRL and Physics of Plasmas); “Issue Highlights” in two GRL issues; and were the topic of 6 separate press releases generating media attention with an audience of millions. Discoveries highlighted in the above press releases and the direct alignment of THEMIS goals with the objectives and focus areas of the Heliophysics Discipline herald the mission’s tremendous potential.

The highest quality data, analysis code, and documentation are routinely available on the main web page (http://themis.ssl.berkeley.edu/) and served via an increasing number of mirror sites (France, Japan, Canada, etc). Level 2 products are SPASE compatible and are routinely released to NSSDC via file transfer. THEMIS supports software users with a “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 semiannually at major meetings.

The THEMIS extension is not only the first clustered equatorial constellation to explore the inner magnetosphere but is highly complementary to current and upcoming heliophysics missions. Working with ARTEMIS, Cluster WIND and Geotail traversals further out in the tail or in the solar wind, THEMIS enables a comprehensive exploration

<p>| Table 1A: THEMIS-at-a-glance: Prime (FY08-09) and Extended (FY10-14) THEMIS Science vs. Mission Objectives |</p>
<table>
<thead>
<tr>
<th>Phase</th>
<th>Abbr</th>
<th>Time Interval</th>
<th>Prime mission: P1, P2, P3, P4, P5</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coast</td>
<td>Coast</td>
<td>Jul. 07-Oct. 07</td>
<td>5-probes &quot;string-of-pearls&quot;, APG=14.7RE</td>
<td>Commissioning &amp; Calibration Bonus: Boundary waves/FTEs</td>
</tr>
<tr>
<td>First Tail</td>
<td>T1</td>
<td>Dec. 07-Apr. 08</td>
<td>APG=10,12,19,5,31 RE, once/4days</td>
<td>Substorm onset</td>
</tr>
<tr>
<td>First Dayside</td>
<td>D1</td>
<td>Jul. 08-Oct. 08</td>
<td>APG=11,12,19,30.7 RE, once/8days</td>
<td>SW coupling, subsonar mpause</td>
</tr>
<tr>
<td>Second Tail</td>
<td>T2</td>
<td>Jan. 09-Mar. 09</td>
<td>APG=12, 12, 12, 19, 31 RE align once / 4 days</td>
<td>Substorm onset, Macroscale interactions</td>
</tr>
<tr>
<td>Second Dayside</td>
<td>D2</td>
<td>Jul. 09-Oct. 09</td>
<td>APG=12.9, 11.6, 11.6, 19.5, 30.4 RE align every 8 days</td>
<td>SW coupling, flanks</td>
</tr>
<tr>
<td>Whole Mission</td>
<td>R</td>
<td>Throughout mission</td>
<td>Two passes per day / probe through radiation belts</td>
<td>Sources/sinks of particle populations, track injections</td>
</tr>
<tr>
<td>3rd Tail</td>
<td>T3</td>
<td>Mar. 10-May 10</td>
<td>dZ=1000km, dR = 5000km daily</td>
<td>Thin currents, Instabilities</td>
</tr>
<tr>
<td>3rd Dayside</td>
<td>D3</td>
<td>Sep. 10-Nov. 10</td>
<td>dZ=3000km, dR=5000km, daily</td>
<td>Asymmetric Rx microphysics</td>
</tr>
<tr>
<td>4th Tail</td>
<td>T4</td>
<td>Apr. 11-Jun. 11</td>
<td>dZ=3000 km, dR=1000 km, daily</td>
<td>Thin current sheets, turbulence</td>
</tr>
<tr>
<td>4th Dayside</td>
<td>D4</td>
<td>Oct. 11-Feb. 12</td>
<td>dZ = 3000 km, dR=5000 km, daily</td>
<td>Rx response to drivers</td>
</tr>
<tr>
<td>5th Tail</td>
<td>T5</td>
<td>May 12-Aug. 12</td>
<td>dZ=5000 km, dR=5000 km, daily</td>
<td>Pressure gradients, Drifts</td>
</tr>
<tr>
<td>Inner Magnetosphere</td>
<td>IM4, IM5</td>
<td>Between Tail and Dayside Phases</td>
<td>3-probes &quot;string-of-pearls&quot;: ~500–5,000km separations along-track</td>
<td>Strong E- field, wave effects on particle source/losses</td>
</tr>
<tr>
<td>Tail/Dayside Inner Magnetosphere</td>
<td>T6/IM6 /D6</td>
<td>Oct. 12-Sep. 13</td>
<td>Along track separation: 4hr, 8hr, 12hr</td>
<td>Coupling of inner magnetosphere to night-time injections, magnetopause oscillations</td>
</tr>
<tr>
<td>Tail/IM7 /D7</td>
<td>Oct. 13-Sep. 14</td>
<td>Along track separation: 8hr, 8hr, 8hr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>Abbr</td>
<td>Time Interval</td>
<td>ARTEMIS: P1, P2 (if approved).</td>
<td>Use as Ancillary:</td>
</tr>
<tr>
<td>Translunar Injection</td>
<td>TLI</td>
<td>Oct. 09-Oct. 10</td>
<td>Translunar orbits to capture into LL1,LL2</td>
<td>Mission Ops, Calibration, Low Priority Solar Wind</td>
</tr>
<tr>
<td>Libration</td>
<td>LL12</td>
<td>Oct. 10-Apr. 11</td>
<td>dR_{p1,p2}=5-20RE at moon, i.e., at 60± 4RE</td>
<td>Routine Solar Wind and Tail Observations from 2 points.</td>
</tr>
<tr>
<td>Lunar Orbit</td>
<td>LO</td>
<td>Apr. 11-Oct. 14</td>
<td>dR_{p1,p2}=0.1 - 6RE at moon: (60± 4RE)</td>
<td></td>
</tr>
</tbody>
</table>
of the Sun-Earth system as it links particle and energy sources to the near-Earth environment. The admittedly demanding mission design requiring inter-spacecraft separations of a few hundred km (i.e., comparable to that of Cluster and MMS missions) is achieved with an efficient, highly integrated science and operations team at a fraction of the cost compared to similar capability missions. THEMIS’s scalable, platform-independent data processing and analysis architecture has already incorporated GOES and NGDC ground observatory data and is planning to incorporate STEREO, ERG and Orbitals data into a “grass-roots” collaborative architecture, akin to the solar community’s “solarsoft”. THEMIS uses Heliophysics resources in efficiently to answer the discipline’s outstanding questions (Table 2A).

By funding THEMIS, the first equatorial, clustered constellation, NASA expands the frontiers of knowledge in the area of substorm and magnetopause transient coupling to the inner magnetosphere and advances our understanding of radiation belt dynamics. THEMIS is a cornerstone of NASA’s Heliophysics Great Observatory, a link between planned international missions and a key component in NASA’s quest to understand the Sun-Earth coupling during the upcoming solar maximum.

Figure 1A. THEMIS baseline and ARTEMIS missions. THEMIS and ARTEMIS have different science goals and technical needs and are being evaluated separately.

2. Overview: Past, Present and Future

The extended THEMIS investigation represents a natural evolution of the Heliophysics discipline in the heels of the scientific progress made during the prime THEMIS mission. Beyond substorm timing, it is a quest for a synthesis of how the near-Earth magnetosphere, the most important region for space weather phenomena, operates as an integrated system. To better explain THEMIS’s future directions and capabilities we need to first look at its most recent accomplishments.

Following launch on February 17, 2007, the THEMIS probes first coasted in a ‘string-of-pearls’ configuration with an apogee of 14.7 Re (Figure 2A). That was a unique period of 500-5000km separations, revealing details of FTEs and surrounding flows, the structure of the magnetopause current layer, and the pressure gradients associated with magnetopause transients despite the un-optimized burst mode data collection and incomplete instrument commissioning.

Figure 2A: “Coast phase” showing early “string-of-pearls” configuration: the first “clustered” THEMIS configuration resulted in >30 publications and significant lessons learned.

Figure 2B: Sun-Earth alignments during the first and second Tail seasons (T1 and T2) as well as the first and second Dayside seasons (D1 and D2). Orbits are maintained at multiples of a sidereal period to maintain conjunctions with ground observatories. Also see Table 1A.
From September to December 2007, the THEMIS probes moved into their individual orbits (Figure 2A). By January 11, 2008, final instrument deployment and commissioning were complete on the last (backup), probe P5. In the ~2 year-long prime mission since then, the THEMIS team obtained the observations needed and accomplished its mission objectives. Repeated probe alignments along the Sun-Earth line (Figure 2B; Angelopoulos, SSR, T2008) over a network of ground based observatories (Figure 2C; Mende et al., SSR, T2008) provided the crucial information needed to discriminate between previously proposed causes of substorm onset, including Rx, current disruption, and other mechanisms.

At onset, the most equatorward auroral arc brightens and moves poleward. The inside-out (or “current disruption”) model for substorms predicted that disruption of the near-Earth current sheet by an as yet unknown plasma instability initiates the brightening, while a tailward-propagating rarefaction wave triggers reconnection in the mid-tail at distances some 20 to 30 \( R_E \) from Earth (Fig. 2D, left).

By contrast, the outside-in (or “reconnection”) model invokes mid-tail reconnection (Fig. 2D, right), which launches earthward-moving bursty bulk flows. The flow bursts brake when they encounter the strong magnetic fields within the inner magnetosphere, resulting in flux pile-up and a magnetic field dipolarization. A substorm current forms where cross-tail (dawn-to-dusk) currents are diverted into the ionosphere by inertial currents or the build up of a north-south gradient of plasma pressure.

On the basis of 3 substorms from the 1st tail season, it was already possible to establish the sequence of events leading up to substorm onset: Clear evidence of reconnection preceding onset was identified for those events (Figures 2Ea and 2Eb, Angelopoulos et al., Science, T2008). Surprisingly, the details of neither of the two expected models were correct: Auroral brightening was started very quickly, i.e., less than 2 minutes after the initiation of tail reconnection, and preceded near-Earth current disruption. A number of studies since then verified the same sequence (Gabrielse, et al., JGR, T2009; Liu et al., JGR, T2009; Pu et al., JGR, T2009 etc.). This means that the first indication of onset is likely due to Alfvén wave - accelerated electrons emanating either at the Rx site or close to it.

The coupling of Rx energy into the ionosphere is an active area of research by at least three groups (UCLA, UMin, UMD). In all models Alfvén waves play a key role in the first indication of onset, by resulting in auroral brightening well before the flows arrive at the inner edge of the plasma sheet. This re-opens the mapping question: Even nowadays, when looking at where the onset instability is using ground imaging alone, it is very tempting to conclude that it is a process starting deep inside Earth’s inner magnetosphere (e.g., Rae et al., JGR, T2009). Is the mapping prior to substorm onset so severely distorted that auroral arcs map to the mid-tail region?
(Kubyshkina et al., JGR, T2009), or is the arc brightening a consequence of yet another process, that occurs immediately after reconnection?

Figure 2Ea: THEMIS results from the 1st tail season: Tail reconnection precedes auroral intensification onset, which – in turn – happens prior to near-Earth dipolarization.

Figure 2Eb: THEMIS 1st tail season (2008) observations, showing that Auroral Intensification (TAi) is delayed relative to reconnection (Rx); but precedes current disruption (CD).

We now think we have the answer: First, the recent observations of North-South red arcs in association with auroral brightening (Kepko et al., GRL, T2009) suggest that precursor activity is possible in the ionosphere, reminiscent of the known signature of fast tail flows (Sergeev et al., 2000; Nakamura et al., 2001).

Figure 2F: THEMIS probes during the 2nd tail season, during detection of sharp dipolarization fronts.

Figure 2G: THEMIS showed that sharp dipolarization fronts (Bz_gsm increases embedded within bursty flows) correlate well with AE index during substorms. These structures flow self-similarly from the mid-tail to inner magnetosphere. Kinetic in nature, they affect the magnetosphere globally.

Second, the sharp dipolarization fronts which are embedded within bursty bulk flows correlate well with AE index increases (Fig. 2F, 2G, Runov et al., GRL, T2009). Dozens of them have been captured on THEMIS by now, propagating from distances beyond 20Re to <10Re in the inner magnetosphere. Even though flows may exist prior to the large scale global onset and may correlate with minor auroral intensifications, it is only when flow bursts are accompanied by dipolarization fronts that the transport has a strong effect on AE. These “dipolarization bursts” represent the tail signatures that correlate best with the
development of a global substorm current wedge. And since they are under-populated flux bubbles they can penetrate easily toward Earth consistent with proposed ideas on low entropy bubbles (Wolf, 2003).

Figure 2H: THEMIS observations of double layers and phase space electron holes within bursty bulk flows in conjunction with Bz fluctuations (Ergun et al., PRL, T2009).

The above tail and ionospheric observations show how the substorm trigger (Rx) site couples energetically with the inner magnetosphere via bursts of dipolarized flows. The sub-gyroradius scale size of the dipolarization fronts and the intense waves encountered within them (Sergeev et al., GRL, T2009) suggest a kinetic treatment for their generation and evolution. Embedded within the bursty flows, and often correlating with the dipolarization fronts, are double-layers and electron holes (e.g., Sergeev et al., GRL, T2009, Ergun et al., PRL, T2009; Andersson et al., GRL, 2009). These had previously been observed on Geotail and POLAR at the plasma sheet boundary layer, and on FAST above the ionosphere, but THEMIS’s deliberate, prolonged residence in the equatorial plasma sheet has revealed their preponderance also at the neutral sheet, within bursty bulk flows, and all the way out to the mid-tail distances, near the mid-tail reconnection.

More recently, Nishimura et al. and Lyons et al. (JGR in review, 2010) examined hundreds of substorm intensifications, and have generalized the Kepko et al., (JGR, T2009) results. They report that north-south arcs protruding into the pre-existing stable pre-onset arc precede most onsets by 2-8min (Figure 2I, courtesy of Y. Nishimura). Incoherent scatter radar observations indicate reduced ionospheric E-region densities in most precursor equatorward flows. To the extent that these are the ionospheric counterparts of the dipolarization bursts, they confirm the THEMIS tail observations and extend them using a global, ground-based perspective.

Figure 2I: THEMIS GBO observations of a north-south arc development preceding substorm onset. Hundreds of similar observations and their magnetospheric counterparts, fast dipolarized flow bursts, point to the importance of the near-Earth region as the point of conversion of the kinetic energy from reconnection to dissipation energy in the auroral ionosphere. Kinetic in nature, dipolarized flow bursts interact with each other and the pre-existing plasma there, with global consequences.

The global onset is, however, a collective phenomenon: recent tail observations indicate that substorm current wedge development comprises the superposition of multiple dipolarized flow bursts. These bursts interact with each other and with the inner magnetosphere: they recoil due to pressure gradients (Panov et al., GRL, T2009), set the inner magnetosphere into vortical motion (Panov et al., T2010, submitted), and spray accelerated particles drifting in the radiation belts.

How does the evolution of these dipolarization bursts – in the kinetic regime – result in the development of a
global current wedge in the inner magnetosphere and the associated substorm expansion phase? Is there an interchange or a cross-field current instability involved in this process, or is the global substorm simply a superposition of incoming dipolarization fronts? This is clearly the next important question in substorm physics.

The question has not been properly addressed because (i) the connection between the mid-tail and inner magnetosphere could not be credibly established prior to the recent THEMIS observations, therefore the question could not be properly posed and (ii) until now there has never been an equatorial clustered constellation with prolonged residence near the neutral sheet. Equatorial orbits with inclinations ~<10° like those of THEMIS are crucial, in particular just prior to substorm onset when the current sheet thins.

Throughout FY10/11/12 the THEMIS team will continue to lead the magnetospheric community on its journey of exploration and discovery. It is important to understand the current structure and radial pressure gradients within the dipolarization fronts, in order to determine how they interact with the pre-existing cross-tail current sheet and neighboring Earthward-moving or recoiling flow bursts. Simultaneous observations of the cross-tail currents densities (Jy) associated with both the horizontal cross-tail current sheet and the vertical sunward-propagating dipolarization fronts are needed to evaluate the growth rate of the cross-field current instability properly (Lui, JGR, 1994). To obtain these observations the THEMIS probes will be repositioned into a clustered meridional configuration (Figure 2J), providing simultaneous measurements of the horizontal and vertical gradients needed to calculate the cross-tail currents densities within the horizontal cross-tail current sheet and the vertical dipolarization fronts. Radial separations will be comparable to the scale size of the incoming dipolarization front current layer (500km). Vertical separations will be comparable to the dipolarization front curvature and the scale-size of the pre-existing cross-tail current sheet (1000-5000km), in order to optimize measurements of the horizontal current sheet current density (Zhou et al., JGR, T2009).

The two past years of THEMIS dayside observations have also enabled detailed studies of the pre-conditioned solar wind’s interaction with the magnetopause, resulting in a number of surprising discoveries. Kinetic processes within the foreshock result in the formation of hot flow anomalies (HFAs) at the intersection of certain interplanetary discontinuities with the bow shock, and these HFAs can in turn elicit extreme undulations (5R_E) of the magnetopause boundary (Eastwood et al., GRL, T2008; Jacobsen et al., JGR, T2009). The observations indicate that some otherwise unremarkable solar wind tangential discontinuities can have enormous effects on the magnetopause, magnetospheric magnetic field, ionospheric convection, and ionospheric currents.

Since reconnection on the dayside magnetopause controls the flow of solar wind energy into the magnetosphere, and reconnection in this location is generally asymmetric (in the sense that magnetic fields are smaller and densities larger than those in the magnetosphere), it is important to understand the nature of asymmetric reconnection at the magnetopause. Simulations for asymmetric conditions predict reconnection rates, X-line locations, and outflow densities and velocities that differ strikingly from those in the symmetric case (Cassak and Shay, 2007). The differences arise due to strong radial density gradients at the magnetopause. These are at the heart of THEMIS’S and the Heliophysics Discipline’s goals to understand both reconnection and solar wind magnetospheric coupling. Advances in this area during the
next two years will aid in planning the MMS mission, which will visit the same region in 2014.

Figure 2K. THEMIS dayside configuration in FY10/11/12, in GSE coordinates (side view from pre-noon sector; Sun is to the right). Orbits are same as at the nightside. Radial separations increase from ~500km (the magnetopause current layer size) in the first year to 5000km the second year, comparable to the size of the low latitude boundary layer.

The THEMIS spacecraft will reach the dayside with the same orbital configuration they had on the nightside, a configuration ideal for addressing long-standing questions regarding the nature of solar wind magnetosphere coupling and the nature of asymmetric reconnection (Figure 2K, Table 1A). Small-scale radial separations (on the order of the magnetopause current layer thickness) via long residence times in the vicinity of the subsolar magnetopause in FY11 will enable observations of density gradients and its effects on reconnection. Larger radial spacecraft separations in FY12 will enable simultaneous measurements of upstream conditions and reconnection jets, validating or negating model predictions. During both years probes P4 and P5 with be separated only in the Z-direction, either bounding or lying on the same side of the reconnection line, testing the asymmetry of reconnection outflows or determining how outflowing electron beams vary as function of X-line distance (Figure 2L).

The THEMIS extended phase provides the first opportunity to make the optimal observations from the required closely clustered observations on a routine basis: Although the THEMIS probes were closely spaced during their initial ‘coast’ phase, burst-triggers enabling full resolution distributions measurements were not yet optimized. The four Cluster spacecraft on the other hand, lie in orbits that traverse the subsolar magnetopause rapidly, resulting in infrequent observations at that location. Together with solar wind monitors (including, if approved, ARTEMIS which will often be ideally positioned directly upstream), THEMIS will be able to characterize the nature of reconnection under a variety of solar wind and magnetosheath conditions and in particular validate theoretical models for asymmetric reconnection.

Figure 2L. Simulation predictions (Pritchett and Mozer, JGR, T2009) for the antisunward (-X) component of the ideal Ohm’s law expression $E + U_x B_x$ near an X-line on the magnetopause for electrons (top) and ions (bottom). THEMIS will employ 3 closely-spaced probes in the X-Z plane to test the predictions of such models for a variety of magnetosheath conditions.

With regards to the inner magnetosphere: THEMIS has obtained excellent results to date in that region. Pertaining to the basic question of radiation belt dynamics, THEMIS has been able to show that the plasma sheet populates the radiation belts during the course of small storms (the only ones available for study in the solar min conditions in the THEMIS era), but electrons do not remain present for long (Wang et al., GRL, T2008). Rather, chorus waves are excited by the unstable anisotropic electron distributions and the anisotropy is amplified by the differential particle drifts (Figures 2M, 2N). Wave amplitudes throughout the dawn magnetosphere and electron anisotropies maintain marginal stability (Li et al., GRL, JGR, T2009). These observations suggest that waves generated by the injected particles play a very important role in transferring energy to the radiation belts but also possibly in scattering and suppressing relativistic particle fluxes. Recent studies of
both older datasets (Green and Kivelson, 2005, Chen et al., 2007, Turner et al., 2009) and also THEMIS studies (Ni et al., 2010 in preparation) employing re-analysis techniques (Shprits et al, JGR, 2007) have placed renewed emphasis on the importance of wave acceleration for radiation belt electrons. Understanding the nature of the wave growth and its effects on particles requires multipoint wave measurements to separate temporal and spatial evolution of unstable distributions and free energy.

Although the SSTs were built primarily for the plasma sheet, they do not saturate in the radiation belts thanks to the provision of a mechanical attenuator reducing fluxes by factor of 100. GEANT4 modeling and flux comparisons with LANL are very promising (Section 3.4).

Figure 2N: Anisotropy (left) and phase space density (right) of 0.5-2keV electrons seen by THEMIS (Li et al., JGR, T2009). The Sun is to the left and dawn points upward in this plot. Chorus growth should peak on the dawnside, where anisotropies and phase space densities maximize, as observed (Figure 2M).

Summarizing, in FY10/11/12 THEMIS will determine the first instantaneous inner magnetospheric radial phase space gradients together with in situ measurements of waves relevant for wave-particle interactions. THEMIS will address the growth of ULF/VLF and EMIC waves and the effect of these waves on particle energization and loss. Finally it will examine the generation and effects of large electric fields (Cattell et al., 2007, Cully et al., GRL, T2008) on radiation belt particles.

In FY13/14, the THEMIS team will build upon the knowledge gained from its Cluster-like, 2-year “microphysics” phase to investigate sources and sinks of particles and energy on a system-wide scale. Towards that goal, a set of simple, yet compelling orbits is being proposed for FY13/14 (Figure 2P). With along-track separations of 4-8-12hrs in FY13 and 8-8-8hrs in FY14 along their 12RE apogee, 24 hour period orbits, THEMIS probes will routinely be separated azimuthally by distances ranging from 2 to 6 RE in the plasma sheet and the subsolar magnetopause. At least one probe is guaranteed to be at or beyond L~10 at all times. These orbits enable simultaneous phase space density measurements in the inner magnetosphere and at high L-shells. THEMIS will provide source populations not only for its own studies but also for RBSP, ERG and Orbitals.

In the tail, the 2-6RE separations permit critical studies of the azimuthal and radial extent of bursty flows, the development of the substorm current wedge, and the drivers of field-aligned currents, including contributions from individual dipolarization bursts. THEMIS plans to investigate the global effects of injections into the inner magnetosphere from its unique vantage-point.

On the dayside, THEMIS will study the coupling of magnetopause phenomena (e.g. surface waves) to the inner...
magnetosphere. ULF and VLF wave excitation by magnetopause transients and their subsequent propagation will be one of the key goals of this phase.

Figure 2O: Representative THEMIS orbits in a “string-of-pearls” configuration, proposed for FY10/11/12 in the dawn and dusk sectors of the magnetosphere. Separations of the order of 500-5,000 km are planned.

THEMIS will provide the multipoint observations needed to understand the effects of individual injections on ring current and radiation belt formation and decay, i.e., global transport. This requires measuring the injection population and local electromagnetic fields in situ, as well as the consequences elsewhere. But models for particle transport in prescribed fields are only as good as the input electromagnetic fields. Localized, time-dependent electric fields are a likely reason for inconsistencies between modeling and observations (e.g., Angelopoulos et al., 2001). A third probe, either near the source region or at the inner magnetosphere, will help constrain the models, resulting in better understanding of the global environment. Particle flux reconstruction models also rely on our present incomplete understanding of wave-particle interactions. Surpluses or deficits from adiabatic convection will thus be explained by means of local acceleration or losses, and wave measurements will be available to verify these inferences. By synthesizing the information gained from its previous two phases, and concurrent wave measurements, THEMIS will incorporate diffusion, particle acceleration and loss models into particle tracing codes to better understand inner magnetosphere particle dynamics.

The key questions to be addressed in the FY13/14 period are not unique to THEMIS but are at the heart of a concerted effort by NASA’s LWS program (RBSP, BARREL) and its international partners (ERG, Orbitals) to understand the radiation belt environment during the upcoming solar maximum. THEMIS plans to be a key player in that effort by providing: (i) The only available and critically needed source population observations from high L-shells (ii) Much needed information concerning outer magnetospheric drivers from locations at or near the magnetopause boundary (iii) Ancillary observations of particles and fields at 2 additional locations within L=10, and (iv) routine observations of the Sunward component of the electric field which not well determined by RBSP’s axial booms. THEMIS’s radial L-shells and differential precession relative to the other missions will enable instrument inter-calibration. Database and analysis tools exchange with those missions have already started in anticipation of what promises to be a golden era for inner magnetospheric research.

Figure 2P: Representative THEMIS orbits in the proposed configuration for FY13/14 at various local times. Two representative 1st year orbits are shown on the dayside and nightside; they will have along-track separations of 4-8-12 hrs. Two representative 2nd year orbits are also shown at dawn and at dusk; those have along-track separations 8-8-8 hrs. When two probes are close to apogee, inter-probe azimuthal separations will be 2-3 Re the first year and 5-6Re the 2nd year.

THEMIS therefore plans to be a key player in ILWS efforts to understand the radiation belts in the FY13/14 period. Achieving the objectives of its extended phase requires THEMIS to engage the full national/international research community. Recognizing its responsibility to enable collaborative projects to reach their full scientific potential, THEMIS has made its entire high resolution dataset, documentation, and software accessible on-line, and is routinely conducting public demos/workshops on how to use the data. Plans for sharing data and software with international partners are already well under way.

THEMIS has enjoyed notable Public Affairs and Education and Public Outreach (EPO) successes (see Section 9 and Appendix A.). The team has worked intensely on education activities 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-
the development of new 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 of discovery and exploration. Our “YouTube” site, showing launch and deployment, was publicized by NASA Watch, and continues to be heavily visited.

3. Closure on Prime Mission Objectives

During the past two years THEMIS has delivered on its promise to collect the necessary data and perform the science analysis that answers the primary question in substorm research. Despite low solar activity, significant progress has been made towards addressing THEMIS’s “bonus science”, namely determining the source and acceleration of storm time electrons and defining the dayside interaction from the foreshock through the magnetosheath to the magnetopause. The THEMIS team has an excellent track record of delivering on its promises, and is capable of leading the field all three of these research areas: Substorms, Ring Current and Radiation Belt phenomena, and Solar-Wind–Magnetosphere interactions, as will be explained below.

3.1 Magnetotail

The primary objective of the mission was to identify the substorm trigger (Angelopoulos, SSR, T2008; Sibeck and Angelopoulos, SSR, T2008), using at least 4 spacecraft conjunctions within ±2R_E from each other in the Y-direction. Outer probes P1 and P2 at distances ~30 and ~20R_E downtail were required to be <5R_E from the neutral sheet whereas inner probes P3, P4, and P5 were required to be within ±2R_E from the neutral sheet. Using comprehensive instrumentation that measures thermal and superthermal electrons and ions and their moments and electromagnetic fields in the range from DC to 10s of Hz, the five spinning THEMIS probes (see Figure 3A) were required to measure the Reconnection (Rx) and Current Disruption (CD) processes and time their onset relative to substorm onset determined from a set of twenty dedicated Ground Based Observatories (GBOs, see mosaics/movies at: http://themis.ssl.berkeley.edu/gbo/display.py) to better than 30s resolution. All spacecraft, instruments and GBOs performed nominally, providing 3s timing at each location. They enabled THEMIS to determine Rx, CD, and substorm onset for dozens of substorms. A well designed set of Survey and Burst mode captures, triggered on tail dipolarizations, resulted in hundreds of hours of high quality multipoint substorm observations with >50 substorms (http://www.igpp.ucla.edu/themis/events) captured during unique tail alignments.

### Table 3A. List of THEMIS L1 requirements and their closure.

<table>
<thead>
<tr>
<th>L1 Req. #</th>
<th>Title</th>
<th>Compliance</th>
<th>Reference/Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.1.2</td>
<td>Determine current disruption (CD) onset w/ 2 inner probes</td>
<td>Flawless P3, P4 operation, found CD onset location, time, speed.</td>
<td>Angelopoulos et al., SSR, T2008 and all of the above.</td>
</tr>
<tr>
<td>4.1.1.3</td>
<td>Determine reconnection (Rx) time from 2 outer probes</td>
<td>Flawless TH-B (P1), TH-C (P2) operation.</td>
<td>Angelopoulos et al., Sci. T2008; Liu et al., Pu et al., T2009; ...</td>
</tr>
<tr>
<td>4.1.1.4</td>
<td>Tail alignments &gt;10 substorms w/ 4 probes for 2yrs (&gt;188 hrs)</td>
<td>Accomplished by March 2009 (end of 2nd tail season)</td>
<td><a href="http://www.igpp.ucla.edu/themis/events">http://www.igpp.ucla.edu/themis/events</a> 46 events in 2008; &gt;16 events in 2009</td>
</tr>
<tr>
<td>4.1.1.5</td>
<td>Track Rx flows (Rx model), or rarefaction wave (CD model).</td>
<td>Earthward flows (Rx model) tracked. THEMIS finds no evidence of rarefaction wave.</td>
<td>Runov et al., 2009a, b; Nishimura et al. Lyons et al., 2009. All of the above (timing)</td>
</tr>
<tr>
<td>4.1.1.6</td>
<td>Determine pressure gradients, vorticity</td>
<td>Optimal orbits achieved</td>
<td>Grad P: Xing et al., Panov et al., T2009; Curl V: Keiling et al., T2008</td>
</tr>
<tr>
<td>4.1.1.7</td>
<td>Cross-sheet currents from B</td>
<td>Optimal orbits achieved</td>
<td>Zhou et al. JGR, JGR, T2009; ...</td>
</tr>
<tr>
<td>4.1.1.8</td>
<td>Obtain V from ESA and EFI</td>
<td>Routine instrument operations</td>
<td>Keika et al., AG, T2009</td>
</tr>
<tr>
<td>4.1.1.9</td>
<td>Determine K-H, FLR and ballooning waves in tail</td>
<td>Optimal orbits and instrumentation achieved</td>
<td>Gabrielse et al., T2008, Zhu et al., T2009; Ge et al. in review</td>
</tr>
<tr>
<td>4.1.1.10</td>
<td>Cross-field current instabilities</td>
<td>Optimal orbits &amp; instrumentation</td>
<td>LeContel et al, T2009</td>
</tr>
<tr>
<td>4.1.1.11</td>
<td>Source and acceleration of storm time electrons</td>
<td>Optimal orbits and instrumentation achieved</td>
<td>Wang et al., T2008; Bortnick et al., Li et al., T2009; Ni et al., prep.</td>
</tr>
<tr>
<td>4.1.1.12</td>
<td>Nature, extend and cause of magnetopause transients</td>
<td>Two dayside seasons with optimal orbits and instruments</td>
<td>Eastwood et al., Sibeck et al., Oieroset et al., T2008; Jacobsen et al., T2009</td>
</tr>
</tbody>
</table>
THEMIS probes are equipped with comprehensive particle and field instruments measuring ions and electrons from 5eV to >1MeV, and electric (E) and magnetic (B) fields from DC to 8kHz. They provide accurate on board moments and E,B spin fits continuously at 3s spin period cadences, and full distributions, wave spectra, and full 16k Sample/s waveforms at increasing cadence from Slow Survey to Wave-Bursts. Instrument scientists and operators have recently optimized high rate data captures in anticipation of the upcoming small-scale separation phase in FY11/12. All instruments & spacecraft are performing flawlessly.

The THEMIS substorms became the focus of a community-based analysis effort under the auspices of the NSF’s GEM Substorm Focus Group: http://aten.jigpp.ucla.edu/gemwiki/index.php/FG12._Substorm_Expansion_Onset:_The_First_10_Minutes

First results were published in special issues of Space Science Reviews, GRL, and JGR (Figure 3B). First definitive observations of substorm onset timing were published in Science (Angelopoulos et al., Sci. T2008, see Figure 2E). Since then a series of papers have corroborated early results (Liu et al., Gabrielse et al., Pu et al., JGR, T2009). L1 baseline requirements call for determination of:

- Time History of Events:
  - Rx-CD-Onset time relationship
- ...and Macroscale Interactions
  - Rx–CD Coupling
  - Field Aligned Current generation
  - Coupling to high frequency modes

3.2 Time History of Events:

THEMIS observations suggesting that reconnection triggers substorms have been amassing. The routine availability of THEMIS GBO data, useful even under hazy weather conditions, enables excellent onset timing that is more precise than that from more classical methods (Pi2s or AE). Multiple substorm onset identifiers have all been tracked, since they can differ by up to minutes. Specifically, poleward auroral expansions follow initial auroral intensifications by several minutes. AE index increases, if they occur, also generally follow poleward expansions by one or more minutes.
T2009, Sergeev et al., JGR, T2009). Determining how field-aligned currents are generated requires multipoint pre-substorm magnetic field and pressure observations. Improved models are needed to determine the signal time delays and identify the mechanisms that link Rx to the first ionospheric signatures of a substorm. Studies are currently underway to improve magnetic models by mapping low-altitude DMSP and NOAA spacecraft observations of isotropy boundaries and precipitation fluxes to corresponding THEMIS measurements.

In addition to direct observations, indirect evidence for reconnection has been also been derived from THEMIS near-Earth clustered configurations (Sergeev et al., JGR, 2008), current sheet behavior during the development of reconnection topologies, and from comparisons of observed and modeled particle distributions (Figure 3D, from Zhou et al., JGR, T2009).

3.3 Macroscale Interactions:
Identifying the means of interaction between Rx outflows and the inner magnetosphere/ionosphere was central to THEMIS objectives. With regards to Rx and CD coupling, Runov et al. (GRL, 2009) and Sergeev et al. (GRL, T2009) have reported the presence of intense dipolarization fronts moving coherently from the mid-tail to Earth as part of a bursty bulk flow structure. Observations (Figure 2F, 2G) show density-depleted structures propagating at ~300km/s to the inner magnetosphere, carrying significant amounts of flux. These are the under-populated flux tubes, previously observed by Sergeev et al. (1996) and theorized by Chen and Wolf (1993) to explain bursty bulk flows (Angelopoulos et al., 1992). The important aspect of the Runov et al. observations is that the dipolarized flow bursts have now been detected propagating inward from the mid-tail (Figure 3E), thus unequivocally linking them to reconnection in the form of the sharp kinetic fronts predicted by recent simulations (Sitnov et al., 2009).

Figure 3D. Ion distribution functions before (top), during (middle) and after (bottom) reconnection (Rx) in the XYDSL plane (XDSL=XGSE, YDSL=YGSE). Left panels: 3s cadence data showing duskward drifting (meandering) ions and (after Rx) ions also escaping tailward. Right panels: modeled fluxes for the E & B fields measured by THEMIS P1 and P2. Only a Rx topology can reproduce the observed distributions (Zhou et al., JGR, T2009).

In addition to direct observations, indirect evidence for reconnection has also been derived from THEMIS near-Earth clustered configurations (Sergeev et al., JGR, 2008), current sheet behavior during the development of reconnection topologies, and from comparisons of observed and modeled particle distributions (Figure 3D, from Zhou et al., JGR, T2009).

Figure 3E. Observations suggest that dipolarized flux tubes embedded within bursty flows during intervals of intense substorm AE activity result from mid-tail reconnection in the plasma sheet. Top: Location of the THEMIS spacecraft during the observations (also see Figure 2G). Bottom: pictorial representation of a dipolarized flux bundle orientation within an Earthward moving flow burst, as determined by minimum variance analysis (MVA) and flow velocity (V_bulk). Hundreds of such fronts exist in the THEMIS database, with more than a dozen captured by THEMIS in a tail-aligned configuration. Tang et al. (JGR, in review)
2010 have shown that the interaction between the flows and the auroral electrojet is strongest when sharp dipolarization fronts are embedded within the flows, likely signifying reconnection extending to the lobes.

Recent observations indicating an incoming bursty bulk flow event in conjunction with a north-south arc prior to onset arc brightening (Kepko et al., GRL, T2009, Figure 3G) confirm this interpretation. A more recent systematic search for the north/south arc signature in hundreds of THEMIS GBO observations of substorms shows that the North-South arcs are, in fact, a repeatable feature of substorm onset (Nishimura et al., JGR in review). Incoherent scatter radar observations of the precursor North South arc (Lyons et al., JGR, in review, 2010) indicate low density (entropy) plasma in the ionospheric signature preceding the auroral onset intensification. The low entropies of the incoming plasma have now been verified not only statistically (Shevchenko et al., JGR, in review, 2010) but also along the path of the dipolarization fronts in the magnetosphere (Runov et al., PSS, in review, 2010). These are the flow burst conditions that allow the bubble to be propelled forward by replacing the pre-existing plasma.

As plasma flows arrive at the near-Earth region, they slow down and recoil due to enhanced pressure gradients (Panov et al., JGR, T2009, Figure 3F). The clustered THEMIS orbits in the extended mission will provide the observations needed to understand the interaction between incoming dipolarization bursts and pre-existing plasma.

With regards to field-aligned current generation in the magnetosphere, THEMIS observations demonstrate that earthward-directed flows generate large scale flow vortices (Figure 3H from Keiling et al., JGR and Ann. Geo. T2009). The vorticity generates sufficient current density to account for a good portion of the substorm current wedge. The intense currents can have visible ionospheric signatures: auroral spirals following auroral expansion. The equivalent ionospheric currents computed from the THEMIS ground based array (Figure 3I) reveal a rotational Hall current component consistent with a upward ionospheric field aligned current within the spiral.

A series of clockwise and anti-clockwise vortex pairs bound successive earthward-tailward flow oscillations rebounding against the inner magnetosphere in the Pi2 frequency range (Panov et al., JGR, T2010). These observations demonstrate a direct coupling between the products of reconnection and the inner edge of the plasma sheet, as well as the ionosphere. They provide closure to the stated goal of the THEMIS mission to reveal the process by which Earthward flow bursts couple to the ionosphere when Rx is the key process triggering substorm onset, an open up the question of what is the physics of this coupling, to be addressed during the extended phase.

Figure 3G. A north-south arc forms poleward from the east-west onset arc 1-2 minutes prior to substorm auroral intensification onset. Arrows in the red-line filtered photometer data (left) indicate the arc, which is also visible in THEMIS white-light data (right). The onset arc is at the bottom of each image, starts to intensify at ~05:30:07UT & begins to move poleward ~30s later.

Finally, THEMIS probes can further investigate the nature and importance of high frequency waves at the inner edge of the plasma sheet during the arrival of the fast flows. THEMIS studies (Figure 3J) have already shown that these waves are produced by field aligned electrons in the aftermath of the arrival of dipolarization fronts. In fact, THEMIS has revealed that such waves are not limited to the inner edge of the plasma sheet. Rather, they are excited at or behind sharp dipolarization fronts, i.e., at the edges of or within dipolarized bursty flows (Sergeev et al., GRL,
The waves are generated as electron distributions become betatron or Fermi accelerated within the depleted flux bundles, exciting whistlers, electron acoustic and electron cyclotron waves. In most cases the front boundary is ~100km – 500km thick, i.e., smaller than the thermal ion gyroradius and comparable to the ion inertial length. It hosts electron instabilities and is supported by a Hall current and an electron pressure gradient.

Figure 3H. THEMIS D, E, A field and flows (top) and their equatorial projection, exhibiting current-generating vorticity.

As discussed in Section 2, THEMIS observations further downtail have revealed that double layers and electron phase space density holes accompany high frequency waves within bursty flows, especially behind dipolarization fronts. Figure 3K illustrates the self-similar nature of the waves within dipolarization fronts as they propagate from earthward from ~20 to ~10R_E (Figures 3E and 2G). It is evident that wave generation is correlated with dipolarization fronts, and therefore the presence or absence of waves depends on whether the spacecraft was directly in the path of (or along the field lines mapping to) the approaching dipolarized bursty flow.

Figure 3I. Vorticity-generated field aligned currents inferred simultaneously with their generator in space, using the THEMIS GBO network.

Figure 3J. Near substorm onset, whistler mode waves at the center of the plasma sheet propagate towards the ionosphere. They are excited by the unstable (field-aligned) electron distributions shown in (f) (LeContel et al., Ann. Geo. T2009).

In summary, THEMIS magnetotail observations provide closure on the mission’s goal to determine the mechanism triggering substorm onset and established the link between mid-tail reconnection and near-Earth phenomena, namely fast flows emanating from the reconnection site. While flows may be present even under moderate geomagnetic activity or growth phase conditions,
it appears that when mid-tail reconnection proceeds to encompass the last closed field line the resultant density depletions in the outflow plasma cause a dramatic change in the propagation characteristics of the flows. As predicted by theory under-populated tubes replace the pre-existing plasma and can thus propagate towards Earth.

**Figure 3K.** Two panels per probe (P1, P2, P3, P4) showing THEMIS E-field spectra (filter bank data, top panels) and the Bz component of the magnetic field (bottom panels) for the propagating dipolarization front of Runov et al., GRL, T2009 (Figure 2G). Detailed analysis of 16kS/s E & B waveforms within this event reveals whistler mode waves, double layers and solitary structures, generated behind the front as it moves inward. Similar structures reported by Ergun et al., (PRL T2009) at locations from the near-Earth neutral sheet to P1 apogee correlate with bursty flows (BBFs) suggesting coupling between Rx outflows and such waves throughout the magnetosphere.

While these results represent a significant advance in substorm research, there needs to be time for the ideas to mature and for the community to scrutinize them through further analysis. In fact, dayside and nightside reconnection are concepts that took many decades to receive acceptance. While THEMIS observations provide compelling evidence for magnetotail reconnection, it will be several years before the field fully embraces the results by re-analyzing published data, and by performing analysis of the many other substorm events available in the THEMIS database. The THEMIS team will continue its full resolution data distribution and analysis software training sessions, in order to promote vetting of its most salient scientific findings.

The kinetic nature of the dipolarization front (~500km scale) and its interaction of the pre-existing plasma deserve further attention from studies employing more appropriate orbit configurations. These new directions for substorm research go beyond the trigger question, and will be answered partly by the THEMIS extended mission (Sections 4 and 5) and partly by MMS.

**Figure 3L.** THEMIS observations during a moderate magnetic storm. Vertical lines indicate times of THEMIS cuts through the inner magnetosphere. Phase space densities are plotted as a function of the first adiabatic invariant, μ, in units of 1keV/5nT = 20MeV/G. Each pair of spectra corresponds a vertical solid line in the top panel (Dst panel). Main phase is the the 3rd panel from bottom. Early recovery phase, a day later, is the 4th panel from the bottom. Ions are on the left, electrons on the right.
3.4 Radiation Belts

As a secondary objective (non-mission driving science) THEMIS proposed to discriminate between various acceleration mechanisms (local versus adiabatic) for radiation belt particles (Sibeck and Angelopoulos, SSR, T2008), using radial phase space density scans of the inner magnetosphere, at times commensurate with the enhancement and depletion of radiation belt electrons.

THEMIS was able to make significant progress towards that goal, despite the weak solar wind conditions during the present solar min and despite the fact that the SST electron detector was not optimized for the inner magnetosphere. Wang et al., GRL, T2009 (Figure 3L) directly observed the inward motion of the plasma sheet as it populated the radiation belt and ring current. The inward motion of the electron plasma sheet results in only a temporary increase of the phase space density of electrons (less than a day) and fluxes recover thereafter to pre-storm values. The results indicate that an inward drift of plasma sheet electrons alone is not sufficient for stably populating the outer radiation belt (contrary to ions in the ring current which remain for many days after the storm).

More recently, the SST detectors on multiple THEMIS spacecraft were calibrated against LANL observations, taking into account electron scattering in the detectors and removing background. A re-analysis of the THEMIS data, together with LANL data, was then performed in accordance with methods applied previously to CRRES data (Shprits et al., 2007). Figure 3M shows results of re-analysis (Ni et al., in preparation, 2010) for a series of 2 moderate storms in 2007. The top panel shows data used for phase space density reconstruction (it is evident that THEMIS probes provide radial scans here from a clustered perspective, during the coast phase, when LANL data were also available). Nevertheless, it is still evident that at THEMIS and LANL conjunctions values of the phase space density are quite similar at all spacecraft, indicating good inter-calibration. The 2nd panel shows a reanalysis of the phase space density with a Kalman filter. Persistent peaks in phase space density cannot be explained by losses at higher L-shells. Rather, they indicate a local acceleration source for relativistic electrons in the inner magnetosphere.

The THEMIS results are consistent with recent work by Green and Kivelson (2004) who reported peaks at L~5 for 1MeV/G electrons, suggesting internal acceleration during active times. Conversely, Onsager et al. (2004) reported positive radial gradients for \( \mu = 6000 \text{MeV/G} \) equatorial electrons at GOES. However, Shprits et al. (2007) and Chen et al., (2007) found persistent peaks near geosynchronous, indicating that the phase space density increases first there, and only later at higher and lower L-shells. Analysis of phase space density gradients using external pressure pulses (Turner and Li., 2008, Turner et al., 2010) also suggested that low energy electrons (<200MeV/G, or 200keV at geosynchronous) diffuse or convect inwards, whereas higher energy electrons may be locally accelerated by wave particle interactions at the inner magnetosphere.

THEMIS in FY11/12 will further test the hypothesis that local acceleration is responsible for the phase space density enhancements of the energetic electrons, by measuring the local gradient in the spectrum and by observing both the relevant waves and wave accelerated electrons simultaneously, as the solar activity increases.

![Figure 3M](image)

Figure 3M. Re-analysis using THEMIS and LANL data after cross-calibration of the energetic particle detectors between the two missions (Ni et al., in preparation, 2010), following techniques similar to Shprits et al., 2007. A phase space density peak near geosynchronous is consistent with wave-accelerated electrons during these moderate storms. See text for discussion.
Figure 3N. Time series of chorus wave power observed on THEMIS-E and hiss seen on THEMIS-D are correlated, as observed in the trough and the plasmasphere respectively (top panel). The correlation time lag (~4s, middle panel) is consistent with ray tracing results on the delay time (bottom panel). Figure from Bortnik et al., Science, T2008.

The importance of waves, in particular whistler mode chorus, for particle acceleration has been recognized by the THEMIS team. Findings reported in Section 2 (Figures 2M and 2N) are particularly pertinent to our understanding of electron acceleration during storms. On the other hand, relativistic electron losses are also gated by chorus and also by hiss waves.

Bortnik et al. (Nature, 2008) showed that hiss waves may be produced by chorus waves, propagating obliquely into the plasmasphere at high latitudes. THEMIS observations (Bortnik et al., Science, T2009) have now verified this hypothesis (Figure 3N). An excellent correlation in wave power between THEMIS-E (P4) observing discrete chorus (in the trough), and THEMIS-D (P3) observing plasmaspheric hiss is consistent with ray tracing of chorus elements into the plasmasphere at the location of THEMIS-D. These observations represent the first confirmation regarding the origin of hiss and allow models of hiss wave generation and their effects on electrons to be incorporated into the radiation belt models. They also showcase the power of the THEMIS constellation to make significant strides in both the microphysics of wave generation and propagation using its proposed string of pearls configuration in the inner magnetosphere in FY11/12, as well as the mission’s potential for exploring cross-scale coupling in the inner magnetosphere from multiple L-shells in FY13/14.

3.5 Dayside

The scientific objective of the tertiary, dayside portion of the THEMIS investigation (non-mission driving science) was to determine the ways by which kinetic effects at the bow shock and in the foreshock modify the solar wind prior to its interaction with the magnetopause, and thus affect solar wind-magnetosphere coupling (Sibeck and Angelopoulos, SSR, T2008). Simultaneous pristine solar wind, foreshock, and magnetopause observations enabled the mission to accomplish its stated goals.

Eastwood et al. (GRL, T2008) reported on the first simultaneous observations of a nascent HFA from both sides of the bow shock, verifying theoretical models (e.g., Schwartz, JGR, 1995) for their origin (Figure 3O). More recently, Jacobsen et al., (JGR, 2009) verified the extreme downstream effects of HFAs (Figure 3P) showing that the passage of an HFA elicited magnetopause undulations as large as 5R_E and extremely large ionospheric convection. Otherwise unremarkable solar wind tangential discontinuities in the solar wind are now shown by THEMIS to have profound effects on the magnetosphere.

THEMIS has also explored the physics of flux ropes and their interaction with the magnetosphere by performing the most detailed modeling of FTEs and their surroundings to date (Zhang et al., Sibeck et al., Liu et al. GRL, T2009); elucidated the physics of the Hall electric field during magnetopause reconnection (Mozer et al, GRL, JGR, 2008); and statistically revealed the evolution of young, crater FTEs into older classical FTEs as they move away from the point of reconnection and lose their plasma content (Zhang et al., in review, 2010).

Future questions regarding the physics of solar wind-magnetosphere coupling center around the efficiency, extent, and nature of magnetopause reconnection. The fundamental question of what controls the rate of asymmetric reconnection is of particular interest to the community now, given recent simulations predicting different coupling efficiency for such boundary conditions.

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community now, given recent simulations predicting different coupling efficiency for such boundary conditions.

The upcoming, clustered THEMIS configuration is specifically designed to address these questions from 100s of km separations, in anticipation of the upcoming MMS mission. Since boundary undulations may drive radiation belt electron acceleration through production of ULF waves, and can also cause loss through magnetopause shadowing, the coupling of energy through the magnetopause to the inner magnetosphere will be the central dayside topic of the proposed FY13/14 extension. These will be described in Sections 4 & 5.

Figure 3O. Hot flow anomalies (HFAs) are kinetic structures that arise from the interaction of certain solar wind tangential discontinuities with appropriate electric field orientations (as shown on top) with the Earth’s bow shock. THEMIS has revealed the birth of an HFA at the shock (Eastwood et al., GRL, T2008).

4. THEMIS FY11/12 Extension

THEMIS is the first multi-probe mission to visit the equatorial magnetosphere with comprehensive instrumentation. Because it hosts some of the most intense space weather phenomena, the equatorial magnetosphere inside of 12RE is of special importance for magnetospheric physics research. Intense auroral arcs magnetically map to the equator inside that distance. In its prime mission THEMIS completed two traversals (Figures 2A, 2B) of this region, providing a wealth of unprecedented observations at macroscale (1 to 10s of RE) separations. Establishing substorm chronology and macroscale interactions between the Rx and CD regions, THEMIS has also revealed the importance of kinetic processes, such as sharp dipolarization fronts and waves, in driving energy transport both globally and also into the inner magnetosphere. On the dayside, the microphysics of reconnection at the subsolar magnetopause lies at the heart of the Heliophysics Discipline’s goal to understand the coupling of solar wind energy to the magnetosphere.

Figure 3P. Effects of a hot flow flow anomaly on the magnetopause (Jacobsen et al., JGR, T2009).

During FY11/12, THEMIS will employ novel inter-spacecraft separations in the XZ plane to address key research problems in the dayside and nightside magnetosphere (see Figures 2J, 2K, in Section 2). At separations ranging from the thermal ion gyroradius (~100s of km) to scales associated with the local field line curvature at the nightside (several ~1000 km) it will address fundamental questions pertaining to the dynamic interaction of dipolarized flow bursts with the near-Earth current sheet. At inter-probe separations ranging from an ion gyroradius up to the width of the magnetopause current layer at the dayside (~200 to 1000km) it will address the nature of asymmetric reconnection and electron acceleration. During the dawn/dusk seasons, THEMIS probes will be positioned into a “string-of-pearls” formation with inter-probe distances from 100s to 1000s of
km to determine the role of waves and strong electric fields in radiation belt and ring current dynamics.

None of the questions above could be answered by any prior mission, including THEMIS-prime and Cluster (Cluster’s polar orbit only crosses the equator inside 4 and outside 12RE). Analysis of the aforementioned processes at small separations distances will permit better planning of orbits and spacecraft/instrument modes for the forthcoming visits to the equatorial magnetosphere by RBSP at the end of FY12 and MMS after FY14 with similar or even smaller inter-spacecraft separations.

The THEMIS extension is aligned with all three Heliophysics objectives: 1. (to understand the flow of energy and primary matter…) 2. (to explore fundamental processes…) and 3. (to define origins and societal impacts …). It is critical for the success of Heliophysics in Focus Areas #3. and #4. (to understand magnetospheres and the space environment) in the next 2 years as it is the only mission observing routinely the inner magnetosphere from the most important, equatorial perspective.

THEMIS’s extended mission will have the instrumentation and inter-probe separations needed to systematically fill a gap in our observations of the plasma sheet, the sub-solar magnetopause, and Earth’s ring current and radiation belts at scales ranging from ion inertial length to a few gyroradii. The proposed extension is a natural evolution of the prime phase’s macroscale separations to a regime where key kinetic processes operate in the equatorial magnetosphere. THEMIS carries the Cluster legacy into an important region of space never visited before from such vantage point and serves as a pathfinder for RBSP and MMS.

4.1 Magnetotail science

The inner edge of the plasma sheet, the region between 7 and 12RE, is a region crucial to space physics. It is where both stable and dynamic auroras likely map, it hosts the strongest currents supporting the magnetotail and it is where the fast flows resulting from near-Earth reconnection deposit their energy. Particle heating and electromagnetic fields generated within this region feed into the inner magnetosphere and affect the storm-time evolution of the ring current. Observations on the scales relevant to its dynamic evolution are needed to understand this region. The extended THEMIS baseline mission will employ sub-RE kinetic-scale, inter-probe spacings and, for the first time, simultaneous radial and Z-separated measurements to study the nature and stability of the near-Earth current sheet and the evolution and dissipation of fast, transport-efficient, Earthward flows.

4.1.1 Interaction of dipolarized fast flows at/with the inner edge of the plasma sheet. High-speed flows carry plasma, energy and magnetic flux Earthward. THEMIS has shown (Section 3) that sharp ion-inertial-length scale-size currents bound the intense magnetic flux bundles with reduced plasma content that lie within these flows. These kinetic structures are critical for flow propagation. The flows stop at locations where the flux tubes have entropy comparable to that of the surrounding media, i.e. near the transition region between dipole-like to tail-like fields at distances some 7-10 RE from Earth. Along the way, and most intensely where the flows stop, the incoming plasma transfers energy into local waves, particle heat, turbulence, or radiates that energy to the ionosphere via field-aligned currents. But how does this interaction of the incoming fast flows and dipolar plasma take place? Is it a result of a new, interchange type or higher frequency CD-type instability, or simply due to a redistribution of pressure and curvature forces? And how is the interaction related to auroral expansion, resulting in the most intense substorm currents into the ionosphere?

Understanding the deceleration of the incoming plasma by the forces that act on it requires careful modeling of the magnetic field topology and its gradients, and modeling 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 simultaneously from satellite pairs at radial and \( Z_{\text{gsn}} \) separations are needed. The extended THEMIS mission will provide such observations for the first time in this key region of space. With the help of LANL, GOES and Geotail (when available at distances 10-15RE) 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 the measurements from other satellites. The THEMIS extended mission will use its radial and Z-separated probes at 7-12 RE to determine the nature of the interaction between dipolarized flow bursts with each other and with the ambient plasma sheet during the course of substorms.
Turbulence is expected to play an important 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. Unlike in the solar wind, where advected turbulence is a reasonable approximation, the field fluctuations in the plasma sheet evolve on time scales comparable to those for advection. Multiple spacecraft are needed to distinguish between Doppler-shifted (spatial) and ambient (temporal) power fluctuations. Multipoint observations over separation distances ranging from 0.1 to 1\( R_E \) are crucial for evaluating the dissipation range of plasma sheet turbulence and its role on conversion of flow energy to heating. The extended THEMIS mission will correlate particle and field measurements at radially separated probes to determine the dissipation range of plasma sheet turbulence and its role in particle heating during fast flows.

4.1.2 Near-Earth current sheet stability and dynamics. The inner magnetosphere drives the field-aligned currents that are responsible for most of the energy deposited in the ionosphere during a substorm. The process is phenomenologically described as a “diversion” of the cross-tail current. It is thus critical to understand how the cross-tail current evolves as the incoming flows arrive and interact with the plasma. For typical current sheet thicknesses (5000km) and densities (~1-5nA/m²) energetic particles drifting duskward carry the cross-tail current. At dynamic times, which are the most interesting, the current sheet thins (<1000km) and even thermal ions of comparable gyroradius execute Speiser orbits and quickly leave the thin current sheet (Figure 4A). Other populations support the current at those times (Mitchell et al., 1990; also Zhou et al., in preparation, 2010). Dipolarization fronts with currents typically ~10-100nA/m² play a significant role in current redistribution. Understanding the dominant current carriers, the plasma populations that support them, and their interaction with the incoming flows 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. That bifurcation may be a key aspect of current sheet destabilization during storms and substorms [Battarchjee et al., 1999]. Current bifurcation and filamentation down to 100s of km has been observed by Cluster beyond 15\( R_E \) 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 7-12\( R_E \). THEMIS’s prime mission Z-separations in T2 are ~1\( R_E \), and thus provided only an average current density. 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 1\( R_E \), are ideal for near-Earth tail studies of current bifurcation and filamentation at active times, and determining the importance of these phenomena for tail dynamics.

The diversion of the cross-tail current sheet to feed the substorm field aligned currents implies that the two current systems are coupled. The nature of this coupling 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 linkage 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 mission provides such separations over a range of resolutions for the first time (Table 1A). The field aligned current produced by the diversion of the cross-tail current can thus be measured, and mapped to the auroral altitudes.

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. At separations ranging progressively from ion inertial lengths (100s of km) to ion gyroradius and field line curvature scales (1000s 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 at active times.

4.2 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 \( R_E \) and outer probe distances of 1-2\( R_E \). The observations revealed the remote (Figure 4B) and internal structure of FTEs, and the nature of the Hall electric field at the magnetopause (Figure 4C).

Following its 2 year prime mission which employed 1-2\( R_E \) separations to study the relationships between magnetopause transients and solar wind features, THEMIS will be poised in the FY11/12 extended phase to address critical, unanswered questions pertaining to the reconnection efficiency, X-line location, reconnection jets and the structure of the current layer from smaller scale separations and completely new vantage points. Near the subsolar magnetopause, THEMIS will use inter-probe separations comparable to the thickness of the magnetopause (~500-3000 km) in the radial and ~3000-5000km in the Z direction to study the microscale structure of asymmetric reconnection (with unequal densities and fields on the two sides), the magnetopause current layer, magnetic islands, and particle energization in them. Such Z-separated orbits have not been obtained before by THEMIS or other missions at the equatorial magnetopause.
Recent simulations indicate that asymmetric reconnection differs greatly from symmetric in terms of reconnection rate, 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. This happens because of a diamagnetic drift of the X-line in one of the outflow direction, at a speed higher than the ion Alfvén speed. This prohibits the Alfvénic outflow jet from coupling to the X-line and suppresses reconnection. Spacecraft separations in the X direction normal to the magnetopause and Z direction along the magnetopause will enable THEMIS to (i) determine the density gradients across the magnetopause needed to calculate predicted drift velocities, (ii) time the drift motion of reconnection lines observed, and (iii) identify the presence or absence of reconnection outflow jets. Agreement with predictions would provide direct evidence for an important condition controlling the most common type of reconnection.

With its Z-separated probe capability THEMIS will determine how the structure of the outflow region varies with distance from the reconnection line. Large-scale reconnection layers are expected to break up into a hierarchy of flux ropes and then reconnect in a turbulent manner, resulting in complex reconnection current sheets [Daughton et al., 2009]. Contrast that with solar wind observations where the reconnecting current sheets are often planar and the structure of the outflow jet is remarkably smooth over hundreds or thousands of ion skin depths [Gosling et al., 2005; Phan et al., 2009]. THEMIS will reveal how the highly structured and transient plasma features in the vicinity of the diffusion region evolve downstream, important not only for magnetospheric physics, but also in astrophysical contexts. Considering that the interacting islands are also sites of efficient electron acceleration, studies of how small scale flux ropes grow, coalesce, and decay is important for understanding how reconnection accelerates electrons to energies far above those associated with the large-scale reconnection flows [Drake et al., 2006; Pritchett, 2006].

Finally, recent kinetic simulations of asymmetric reconnection with a guide field predict drastically different outflow regions north and south of the X-line. An extended electron jet emanating from the diffusion region appears only on one side of the X-line [Pritchett and Mozer, JGR, T2009]. Simultaneous observations from THEMIS spacecraft bounding X-lines will verify these predictions during the extended mission.

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.

4.3 Inner magnetosphere science

As preparations for NASA’s RBSP mission continue, the inner magnetosphere is becoming the focus of concerted studies. In its prime mission THEMIS has ascertained that local wave acceleration plays a significant role in the appearance of relativistic, “killer” electrons during the recovery phase of storms. The most effective wave acceleration mechanisms for storm-time MeV electrons are resonances with lower band chorus and ULF waves. Hiss and ElectroMagnetic Ion Cyclotron (EMIC) waves have been identified as a dominant loss process. THEMIS has determined the distribution and growth mechanisms of chorus and hiss (see Section 3) as well as ULF waves (e.g., Liu et al., JGR, T2009).

With experience in “string-of-pearls” operations, advances in burst mode wave captures, and the creation of new data products geared towards wave surveys, THEMIS is ideally instrumented to study chorus, ULF, and EMIC wave-related electron acceleration/losses during storms.
Figure 4D. An EMIC event, on Jun. 29, 2007, seen by THEMIS TH-C, D, E in a string-of-pearls formation. All probes consistently recorded Pc1 magnetic field fluctuations at L shells of 5 - 6.5. THEMIS determined the radial extent in the magnetosphere to be ~1.3 RE. The coherent EMIC waves were seen slightly further out by each subsequent probe pass, but in each case were bounded at high-L by a decrease in density, as determined by the probe potential (Usanova et al., GRL, 2008). Such formations, key for resolving spatio-temporal ambiguities will only be possible again during the THEMIS extended phase.

In FY10/11/12 THEMIS will determine how instantaneous electron phase space gradients are affected by wave-particle interactions. Its “string-of-pearls” configuration with along-track separations of 500km – 5000km will be ideal for distinguishing the spatial extent of the waves in L-shell from the temporal growth of the waves due to the presence of (locally measured) free energy sources (see for example application of these techniques in Figure 4D). Longer term changes in radiation belt morphology due to the stochastic combination of ULF waves (Pc3-5 and EMIC) and VLF acceleration and loss are also possible through simultaneous studies of the dynamics of the radial profiles of electron phase space density. This is especially true in combination with ancillary measurements from Cluster, SAMPEX, LANL and GOES satellites as those measurements become available (e.g., see Figure 3M). The team is taking a pro-active step and including GOES data into its data analysis and distribution system to facilitate such studies. This will be particularly important with the availability of particle data from the new GOES series in March 2010. The proposed analyses of key particle acceleration and loss processes, which drive radiation belt dynamics will prepare the field for the advent of RBSP during the ascending phase of the next Solar Cycle.

In conjunction with ancillary ground and space 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.

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. They are also related to the closure of the ring current through the plasmaspheric trough. Strong storm-time electric fields are often related to sub-auroral polarization drifts, which erode the plasmasphere and create plasma plumes that stretch outward to the dayside magnetopause. Accurate electric field models are essential to determine 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 the 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 0.1-1RE are needed to unravel the sharp density and electric field gradients on the edges of the plumes and to study how substorm electric fields may propagate into and affect the ring current region. The equatorial, string-of-pearls strategy of the THEMIS extended baseline mission is ideal for determining the quasi-static storm-time electric field, its spatial extent, long-term evolution, and its relationship with ground observations of SAPS in the sub-auroral ionosphere. Working with the mid- and low-latitude Millstone Hill, SuperDARN, and Arecibo radar teams, providing ionospheric densities and electric fields, and with ground-based GPS observations of ionospheric densities, we expect to establish the relationships between the strong electric fields observed at their source, near THEMIS, and on the ground. The proposed configuration during the upcoming solar maximum will afford us the opportunity to develop the first truly empirical global electric field model pertinent to the storm-time inner magnetosphere, 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 THEMIS will determine how these fields couple to the ionosphere.

5. THEMIS FY13/14 Extension

By the end of FY12, THEMIS will have determined how waves affect phase space density gradients in the radiation belts, how fast flows interact with the inner edge of the plasma sheet to produce a range of phenomena that affect the inner magnetosphere, and how magnetopause transients are generated and evolve at the magnetopause boundary. During the forthcoming solar maximum in FY13/14, THEMIS will build upon this knowledge to determine the magnetospheric responses to increased solar activity and improve our understanding of space weather.

THEMIS will employ a unique set of simple but very powerful orbits with along-track separations of 4-8-12hrs in FY13 and 8-8-8hrs in FY14, as described in Section 2 (Figure 2P). By design, at least one probe will continuously be measuring fluxes at L~10 or greater, while another one or two probes will be measuring the fluxes in the inner magnetosphere. This strategy will provide the first opportunity to explore comprehensively the cause-and-effect relationships between radiation belt and ring current particle sources (e.g. injections) and sinks (e.g., magnetopause shadowing).

Figure 5A. THEMIS orbits, shown once per 6 months, along with RBSP locations. With an apogee of 12RE and probe separations such that at least one THEMIS probe will be at L>10 THEMIS will provide tremendous synergy to RBSP, as well as international missions, such as ERG and Orbitals.

While the primary goal for the FY13/14 extension concerns inner magnetospheric particle sources and sinks at L~10, the orbits employed for these purposes will also enable significant advances for tail and magnetopause science: In the magnetotail, THEMIS will determine the global evolution of the substorm current wedge; while on the dayside it will systematically address the mechanisms by which magnetopause transients couple to ULF and VLF waves across large scales. Both these goals support the primary emphasis on the inner magnetosphere.

The THEMIS orbit complements those of RBSP, ERG and Orbitals. Figure 5A shows snapshots of RBSP and THEMIS orbits once each 6 months. THEMIS will monitor source populations and loss processes for RBSP at higher L-shells with numerous cross-calibration opportunities throughout FY13/14. With spin plane booms on the ~XYGSE plane, THEMIS will provide more accurate observations of the electric field component along the Sun-Earth line than can be obtained from the axial booms on RBSP, whose spin plane lies in the ~YZGSE plane. The full set of electric field components can be critical for understanding ULF wave polarization and shocks.

5.1 Inner magnetosphere: storm-time science

The radiation belts and ring current are populated by plasma sheet particles convected inwards by large scale convection as well as localized injection electric fields. As particles drift inward their distributions become unstable to waves, which in turn accelerate or scatter the particles, modifying the radiation belt and ring current populations. As particles drift through the plasmapause and plasmaspheric plumes they may interact with other waves that further modify their fluxes. ULF waves excited by solar wind pressure pulses, magnetopause waves or unstable ions injected at dusk also affect radiation belt fluxes through resonant acceleration or diffusion. Finally, pressure pulses and solar wind transients buffet and compress the magnetopause (e.g., Figure 3P) temporarily enabling particles on drift paths deep within the magnetosphere to encounter the magnetopause and become lost, resulting in magnetopause shadowing and negative radial phase space density gradients. Accurate characterization of the processes at low L-shells cannot take place without accurate measurements of the sources and losses at the boundaries. THEMIS will compare local flux and wave measurements at low L-shells with simultaneous measurements of the particle sources and/or magnetopause motion at high L-shells to address comprehensively how the ring current and radiation belts are populated and evolve during storms.

Of particular interest here are nightside injections and their storm-time variants, sawtooth events. Recognized from the dawn of the space age as important for inner magnetosphere studies, injections have defied proper integration into global storm-time models because (1) their source is in the equatorial plasma sheet beyond geosynchronous altitude, where routine measurements are scarce and (2) injections are often localized with an azimuthal extent that varies considerably with time. Localized electric field models have been quite successful in reproducing some aspects of the injections but are far from being incorporated into global transport models. THEMIS’s 3 point measurements at multiple L-shells will enable the first comprehensive investigation of night-time
injections including the associated electric fields. When incorporated into bounce averaged guiding center models and re-analysis models (Figure 3M) they are expected to enable significant advances in understanding and predicting space weather phenomena.

5.2 Magnetotail: global substorm evolution

With simultaneous observations from at least two points on the inner edge of the plasma sheet (~7-10\(R_E\)) separated by large lateral distances (3-6\(R_E\)), THEMIS will determine the collective effect of individual injections (flows and dipolarization fronts) during the course of substorms. The important question here is: how does the large scale substorm current wedge get formed from individual narrow dipolarization bursts (flux pulses) arriving at the inner edge of the plasma sheet? Until now, THEMIS has not had routinely large-scale separations spanning the global azimuthal expansion of a substorm. The new THEMIS observations in FY13/14 will extend results from GOES and LANL at 6.6 \(R_E\) (Nagai et al., 1980, Birn et al., 1997) and open up a unique opportunity for characterizing the global substorm instability at precisely the 7-10\(R_E\) altitudes where arcs likely map and injections are most geoeffective. They will characterize the evolution of the energy and particle sources during substorms/storms, whether they are directly linked to buildup of reconnection ejecta or local instabilities (depending on results obtained in FY11/12). We will work with high resolution GOES magnetometer (data pipeline already established) and particle data provided by GOES scientists who are already THEMIS team members.

5.3 Dayside: coupling of transients

For several hours each day, each THEMIS probe will be at ~12\(R_E\) in the vicinity of the dayside magnetopause. The constellation will be ideal for near-continuous measurements of magnetosheath, magnetopause, and outer magnetospheric boundary transients while one or two probes will be measuring the effects of these transients deeper in the dayside magnetosphere. This unique constellation is ideal for determining the degree to which boundary processes such as reconnection, pressure pulses, Kelvin-Helmholtz waves, Hot Flow Anomalies, and solar wind shocks couple with ULF waves (Pc3-4 pulsations), compression-induced dayside chorus (Li et al. GRL, T2009), and associated hiss (Bortnik et al., Science, T2009). Past THEMIS measurements have not in general been well correlated with inner magnetospheric measurements because P3 and P4 were separated by only ~1 \(R_E\), while P5 was in an 8-day conjunction. However, for a couple of weeks during commissioning phase, in April 2007 large separations were possible resulting in a remarkable observation: Agapitov et al. (GRL, T2009) reported the first direct evidence for Kelvin-Helmholtz waves at the magnetopause boundary driving field line resonances deep within the inner magnetosphere some 5-6 \(R_E\) away. Comparable inter-spacecraft separations will be achieved routinely in FY13/14. The can be used not only to determine the radial profile/frequency of wave power (e.g. Figure 5B) but also their azimuthal wave number.

**Figure 5B.** THEMIS observations of field line resonances in magnetic (bottom 2 panels) and electric (top 2 panels) field data allow complete mode characterization (Sarris et al., GRL, T2008).

In FY13/14 with another probe on the opposite leg of the orbit THEMIS will also be able to determine azimuthal mode numbers, while a 3rd probe near the boundary will monitor ULF drivers.

During FY13, two of the three THEMIS probes will be separated by 3 \(R_E\), while crossing the subsolar magnetopause at geocentric distances of ~11 \(R_E\). This configuration is unique to THEMIS and ideal for determining the nature of magnetopause transients (pressure pulses, FTEs, KH waves). Surface propagation characteristics will be established under a variety of upstream conditions measured by nearby ARTEMIS (if approved) or other solar wind monitors at L1. Therefore, in FY13 THEMIS will be ideally positioned at the magnetopause, able to determine with confidence not only the presence of magnetopause transients but also their nature, generation and importance for solar wind magnetosphere coupling.

In summary, the THEMIS FY13/14 extension will provide critical observations needed to understand the inner magnetosphere’s evolution in response to its boundary conditions during storms. The primary emphasis of THEMIS is on the coupling of the inner magnetosphere to the sources and sinks at the boundaries, which complements RBSP. With science, software and data-exchange links to (and team members on) ERG and Orbits, THEMIS is a key mission for the International Living With a Star program and a cornerstone program of the Heliophysics discipline in the next solar maximum.
6. Other significant results

In addition to the primary mission results described in Section 3, other significant findings are described here as they bespeak of the mission’s potential and the techniques to be used during the proposed, clustered/string-of-pearls orbits in FY11/12 and the solar max orbits in FY13/14.

6.1 Magnetotail

- Westward traveling surge: space signature. The early string-of-pearls configuration allowed the first comprehensive observations of substorm westward traveling surge signatures. The ~250 km/s westward expansion speed measured using finite gyroradius techniques on SST energetic particle observations matched the expansion speed inferred from auroral images (Angelopoulos et al., SSR, T2008). The same techniques will be used to determine the dipolarization front orientations and speeds on a routine basis in FY11/12.

- Substorm motion of plasma sheet inner edge: While in the string-of-pearls configuration, THEMIS observed and modeled the first evidence of rapid (1-2 hr) inward and outward motion of the near-Earth plasma sheet in response to substorm electric fields (Runov et al., GRL 2009). Similar modeling will advance our understanding of substorm coupling to inner magnetosphere during storms.

- Modeling substorm injection fluxes. Using a simple but powerful model for magnetic and inductive electric fields, THEMIS researchers have reproduced particle fluxes injected into the inner magnetosphere (Liu W. et al., JGR, T2009). These tools will be used in FY13/14 to link sources and sinks of inner magnetospheric populations.

- 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 amplitudes as large as the plasma sheet thickness, these waves were seen during storms for the first time. Their importance as a diagnostic or for diffusion will be studied more thoroughly during the upcoming solar max. (Gabrielse et al., GRL, T2009)

- Pi1 pulsations: first signature of ground onset. Careful onset timing points towards Pi1 waves with 12-40s periods as the first marker of substorm onset. These waves are observed just eastward of the substorm meridian, telling us how ionospheric conductivity affects substorm evolution (Milling et al., GRL, T2008). Similar THEMIS GBO array observations will be used for onset determination despite clouds, moonlight, or sunlight as THEMIS orbits precess towards midnight apogees in the summers of FY13/14.

- From solar wind shocks to substorm onset. THEMIS’s string-of-pearls observations and ground array, coupled with observations from a dozen other spacecraft, enabled a comprehensive modeling and observational study of a solar wind shock propagating through the magnetosphere and triggering substorm onset (Keika et al., JGR, 2009). Similar techniques will be used to study CME transient and shock propagation in FY13/14.

6.2 Dayside:

- Turbulent mixing at the magnetopause. THEMIS multi-point observations resolved the k-spectrum of waves at the magnetopause and identified kinetic Alfvén waves as the mode of magnetopause turbulence. (Chaston et al., GRL, T2009). Similar techniques will be used in FY11/12 to study reconnection island formation and coalescence.

- Northward IMF magnetopause coupling. Oieroset et al., (GRL, T2008) used probe separations over several Re scales (coast phase) to show that the low latitude boundary layer becomes very thick under northward IMF conditions. Modeling demonstrated that magnetosheath plasma gained direct access into the magnetosphere via dual lobe reconnection (Li et al., JGR, T2009). This process will be key to understanding storm intensity during the upcoming solar max in FY13/14, when CMEs will have a predominantly south-then-north polarity. A dense plasma sheet followed by southward IMF reconnection results in very geo-effective storms. We will use similar observations and simulations to determine the efficacy of magnetopause coupling and the importance of super-dense plasma sheet entry into the ring current in FY13/14.

- Sheath mirror mode coupling to ULF waves. Nowada et al. (JGR, T2009) showed that magnetosheath mirror mode waves couple to ULF waves inside the magnetosphere via magnetopause oscillations. Given the preponderance of mirror mode waves in the sheath, and the possibility that they trigger bursty reconnection, this may be an important mechanism that need to be further quantified in the extended phase as part of building a comprehensive understanding of magnetopause-inner magnetosphere coupling in FY13/14.

- Surface waves at the boundary. Plaschke et al. (Ann. Geophys., GRL, JGR, 2009) identified magnetopause surface waves as standing Alfvénic “Kruskal-Schwarzschild” surface modes. Their periodicities match ULF frequencies on the ground. Multiple probe observations in FY13 will enable their detailed analysis.

6.3 Inner Magnetosphere:

- Plasmaspheric plumes feeding reconnection. THEMIS’s string-of-pearls formation distinguished spatial from temporal variations of structured plasmaspheric plumes. Adjacent to the magnetopause the plumes form a layer of cold ions partaking in magnetopause reconnection (McFadden et al., GRL, T2009). These ideas and tools are critical to our understanding of asymmetric reconnection using similar inter-probe separations in FY11/12.

- Large amplitude whistlers in radiation belts. Large amplitude whistler mode waves have been observed in the dawn side radiation belts, lasting for days. These waves must be taken into account in radiation belt models, and
will be monitored by THEMIS to determine if they can explain wave-accelerated energetic electrons in FY11/12.

7. Potential for future discoveries
The THEMIS team of scientists, software engineers, instrument and operations personnel is highly integrated. The team works efficiently on delivering its scientific promises (Section 3), fulfilling the aspirations of the Heliophysics discipline through maximizing the scientific return from the THEMIS probes. A prime example of this efficiency is the rapid redesign of the 2nd year of its orbits, to accommodate the unusually thin plasma sheet thickness observed in the 1st tail season, with minimal fuel costs, on target and on-budget. Another example is the development of ARTEMIS and the restructuring of the mission operations center to command the probes to the Moon with no additional costs on the UCB side. The breadth and quality of past achievements pertaining to prime and bonus science objectives, bespeak of a team that analyzes the THEMIS observatory’s data as an integrated suite of multiple space and ground experiments to make transformational progress in Heliophysics. Having identified the substorm trigger, the next step in understanding space weather phenomena is to determine how the most geoeffective reconnection pulses, i.e., the dipolarized flow bursts, drive the inner magnetosphere and related space weather phenomena, such as ring current injections, waves, particle transport and ultimately particle acceleration in the inner magnetosphere. Thus from the closure of the main THEMIS objectives (Sec. 3), to the plans for FY10/11/12 (Sec. 4) and onward to FY13/14 (Sec. 5) we see the natural, albeit rapid, progression of the Heliophysics discipline in the aftermath of breakthroughs in understanding substorms that stemmed from the prime mission. Below are the top reasons for THEMIS’s potential for future discoveries in FY11-14:

• **Location.** Understanding the fundamental mechanisms for particle transport and energy transformation in the equatorial magnetosphere at <12R_E is absolutely essential for making progress in all three primary objectives of Heliophysics (Section 4). The region is a conduit, a driver, or a host of essentially all important space weather phenomena, including growth-phase and active arcs, ionospheric currents and heating, electron precipitation, and the radiation belts. Exploring this region is particularly timely, in conjunction with the upcoming solar max. No other mission has comprehensively studied this region (let alone during active times). THEMIS fills this observational gap with not one but three fully instrumented and completely healthy spacecraft.

• **Relevant science.** THEMIS science lies at the cutting edge of magnetospheric research: In FY11/12 (Sec. 4) THEMIS will study the microphysics of fundamental processes that bear global consequences. The kinetic nature of dipolarization fronts, the stability and dynamics of the near-Earth current sheet, the microphysics of asymmetric magnetopause reconnection and the effect of waves on phase space density gradients are all essential to understand before we can attempt to piece together comprehensive theories of energy and particle transport in the near-Earth environment.

In FY13/14, THEMIS will explore the dynamics of the equatorial magnetosphere from yet another completely new vantage point: that of large scale separations. The science questions addressed (Sec. 5), i.e., how the radiation belts and ring current are populated and energized by local wave growth or particle populations emanating at higher L-shells, are at the heart of the discipline’s quest to understand transport in the Heliosphere. They follow in the heels of a concerted effort to understand fundamental kinetic processes with global consequences in FY11/12 and concurrent with solar max conditions, when moderate to large storms will be common. These questions represent the epitome of the Heliophysics quest to understand space weather phenomena. Given its complementarity with NASA’s RBSP and the international community’s ERG and Orbitals missions, and having already established collaborative efforts with these programs, THEMIS science is not only relevant, but at the forefront of the Heliophysics discipline’s stated objectives.

• **Orbits and instrumentation.** The proposed clustered orbits in FY11/12 are unique, both in terms of spatial scales (ion inertial length) and orientation (along the XZ plane), revealing new and critical physics in the region (Section 4). The orbits in FY13/14 (Section 5) are also unprecedented: they enable continuous monitoring of high L-shells, such that at no time will the effects of CMEs, interplanetary shocks, cold-dense plasma sheet (if at the nightside) escape detection. They will enable continuous evaluation of inner magnetospheric particle sources and sinks. The comprehensive THEMIS particles and fields instruments (Figure 3A) are working flawlessly (Section 8) on all probes and have been calibrated in almost all regions. Absolute calibrations of the SST within the inner magnetosphere were beyond the scope of the prime mission but have started now with considerable success (Figure 3N) and will be complete within the next year. The complete instrumentation package available on THEMIS is unique for this region of space; and even more so considering THEMIS’s multiple platforms.

• **Enabling community science.** The power of the THEMIS constellation lies not just in its team but also in the community’s ability to fully utilize its data, software and human resources. In recognition of this doctrine, the THEMIS team has not only provided its highest resolution data openly, but also provided machine-independent software for seamless data downloads, highly advanced analysis ([http://themis.ssl.berkeley.edu/software.shtml](http://themis.ssl.berkeley.edu/software.shtml)) and recipes (“crib sheets”) on how to conduct research with the data. Semiannual software tutorials are reinforced by a user-support email service and a listserver of latest updates. These permit community feedback and quick
dissemination of code updates. Version-controlled using SVN, this analysis software permits the same data access to the community as the instrument team enjoys, but also represents a grass roots software development and exchange platform, equivalent to the very successful solar community’s “solarsoft”. Thus THEMIS is by design a “community” mission, and this is reflected in its data system, enabling sharing of ideas, data and analysis tools simultaneously. THEMIS continues to evolve this grass roots concept by integrating other mission and ground-observatory data, providing a powerful platform for the Heliophysics observatory. The accelerating pace of community participation (non-col, non-THEMIS funded, first-author publications were 40% of total in 2008 and 50% of total in 2009) shows the success of the THEMIS team in engaging and enabling the community to perform THEMIS research. See: (http://themis.ssl.berkeley.edu click: Publications).

In summary, the THEMIS extended mission’s prime location, the cutting-edge science questions that it will address, its unique orbit design, its 100% operational and fine-tuned instrumentation and its pro-active embrace of the entire science community point towards its promise for future discoveries. Past performance is a solid indicator that THEMIS will deliver on that promise. THEMIS is leading Heliophysics on a journey of exploration of cross-scale coupling of fundamental physical processes in the near-Earth space environment.

8. Technical/Budget

8.1 Technical

8.1.1 Observatory and instrument status As of this writing, the entire THEMIS constellation is in excellent health and performing nominally. The two outer probes are already on their way to their lunar orbits while the inner three probes have just started their extended science operations. In all, after more than 350 individual thrust operations, ~500 shadow cycles, and approximately 3 years in orbit traversing the radiation belts there are no signs of any measurable degradation in performance on any spacecraft or instrument subsystems, including solar array power and battery charge retention. 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 that have been addressed by ground software: (1) As anticipated, sunlight affects two sectors per spin of the SST. It was found in orbit that the large current drawn from the sun pulse does not have an adverse effect on the sensitive SCM, and thus pre-launch planned operations to track and mask the sun electronically have been scrapped in favor of operations simplicity. Instead analysis tools that remove the sun pulse and associated electronic noise have been devised and are widely disseminated to the team and the community. (2) Spin harmonics and 32 Hz noise affect the SCM. This has been corrected by ground software as part of the standard calibration routines. (3) An 11 Hz noise affected the FGM (at ~30pT level, only minor). This has been recently diagnosed as interference from particle sectoring which is sun-pulse-synchronous and has been fixed with an operational workaround: By changing the spin rate of the probes by a few msec the noise band is pushed beyond the FGM frequency cutoff.

Instruments operate in Slow Survey (SS) mode most of the orbit and in Fast Survey (FS) mode during conjunctions (~12 hrs/orbit). Horizontal bars indicate fast and slow survey mode intervals 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).

Automated operations support routine passes. Approximately 17000 passes have been completed to date in lights-out mode. Average downlink performance presently exceeds requirements by 50%, thanks to the ground system performance.

8.1.2 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 run months in advance with nominal planned maneuvers with a quick turnaround reaffirming conjunctions, shadows, and fuel budget. Product generation based on updated ephemerides is fully automated. GSFC flight dynamics provide backup orbit solutions for each probe. Telemetry files are transferred post-pass from the ground stations to UCB, checked and archived. Level 0, 1 and 2 data processing is automated. Instrument scientists (“tohbans”) review survey plots ~1 day after receipt of data on the ground. See 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 USN and HBK stations have been certified and also support THEMIS. The NTR T-1 line from GSFC to the MOC over the Open IONet and 3 voice loops continue to function nominally.

Mission operations. Following the 1st tail season, scientific data analysis indicated that the tail current sheet was thinner than anticipated, resulting in orbit redesign for the 2nd tail season. This was performed with remarkable success. Thanks to the increased familiarity of the operations team with the propulsion and thermal systems, it is now possible to control a maneuver down to a fraction of a single side-thrust pulse, or 10cm/s, which is important for the planned clustered configuration orbits in FY11/12.

Specifically, inter-probe separations of 100s of km will be achieved and maintained in the extended phase, resulting in an unprecedented view of the equatorial
magnetosphere. The planned orbits (Section 2) require but orbit determination and orbit control comparable to those of the Cluster mission, but commensurate with the present knowledge of the THEMIS operations team. Planned manoeuvres in FY13/14 are much simpler and consistent with current practices. Healthy fuel reserves (>150% after accounting de-orbit fuel) for all probes and permit exciting possibilities for joint work with MMS beyond FY14.

**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 the inner magnetosphere goals of the extended mission in FY13/14. Instrument operation staffing levels are assumed as required and as per plan in FY11/12. Significant savings from operational simplicity, automation and familiarity of the team with instrument operations will reduce mission and science operations personnel in FY13/14.

### 8.2 Budget

**8.2.1 Contract history (FY07-today).** Delays in obtaining a Phase E contract from GSFC moderated the early science ramp-up of the THEMIS team. The team used its resources optimally mostly in mission and instrument operations in 2007. The Phase E contract was awarded 15 months after launch (May 2008), at which point operations planning for ARTEMIS commenced. Since the start of the nominal extended phase in October 2009, THEMIS has been operating under prime mission contract extensions. The THEMIS contract ended on-target, despite the addition of significant ARTEMIS operations planning work, which was absorbed through early personnel reductions in the summer of 2009. Since then the science and operations team has been stable and barring unforeseen further contract delays or cash flow issues, it is expected that operations successes will continue and science discoveries will accelerate.

**8.2.3 Equipment.** Funding for Mission and Science Operations workstations and server upgrades, Flatsat upgrades, Berkeley Ground Station maintenance and upgrades add up to approximately $200K/year under Space Communications Services, due to antenna age and criticality of BGS operations.

**8.2.4 Travel.** Between UCB and major subcontractors approximately 40 domestic and 5 foreign trips per year are budgeted for attending major scientific (or operations) meetings, presentation of science discoveries, and UCB-UCLA inter-campus travel for the PI and operations personnel to ensure efficient communications.

### 8.2.5 Major budget items:

- **Space Communication Services:** This includes pass scheduling, flight operations, and ground system support, as well as maintenance and upgrades to the Mission/Science Operations center;
- **Mission Services:** This includes UCB mission navigation, orbit and attitude determination and UCB/UCLA mission design;
- **Science Operations:** Science Data processing, documentation and archival for the specific operational modes and data products of this mission, including ground based observatories, community support, software help line and tutorials;
- **Science Data Analysis:** co-I team funding at GSFC (1), APL (1), UCB (4), UCLA (4), LASP (2) and UNH (1) including computer simulations and comparison of results with probe data. While co-Is are assigned responsibilities on specific instruments, all are expected to analyze data from all instruments; *In-kind contributions* include SSMO Project Management and Services (Ground Network, T1 Line to Berkeley).

### 9. Public Affairs

Our vigorous public affairs program at NASA/GSFC achieved remarkable successes during the past 3 years. This a testament to the team’s commitment and wherewithal to sharing the excitement of space research with the public and reaching large audiences. Press releases or press conferences in the Fall AGU 2007, 2008 and 2009; Spring AGU 2009 and EGU 2009 all resulted in wide acceptance by the media and coverage by the press, including numerous interviews broadcast by BBC, CBC, and NPR, a feature on the NPR program Earth & Sky and dozens of other stations around the world. We gave two presentations at the Maryland Science Center, and again at the Smithsonian. PBS’s Jim Lehrer Newshour (Figure 9A, also: [http://www.pbs.org/newshour/indepth_coverage/science/spacstorms/](http://www.pbs.org/newshour/indepth_coverage/science/spacstorms/)) presented a special report on our E/PO efforts to engage Alaskan students in science and is preparing a follow-up program; while PBS’s NOVA series presented the THEMIS mission in a special episode on space storms (Figure 9A, also see: [www.pbs.org/wgbh/nova/sciencenow/0304/02.html](http://www.pbs.org/wgbh/nova/sciencenow/0304/02.html)). Additionally, press releases tied to publications in Science by Angelopoulos et al., 2008; Bortnik et al., 2009; and Keiling (JGR on “space tornadoes”) also made it into the public media (Figure 9B). Our successes are the best indicator of future promise of delivery on this front.

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<thead>
<tr>
<th><strong>Country</strong></th>
<th><strong>Undergrads</strong></th>
<th><strong>Grads</strong></th>
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<tr>
<td>USA</td>
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Table 8A. THEMIS supports 47 young scientists.
THEMIS currently plans a press release in May 2010, in conjunction with our recent results on recoiling bursty flows, at the EGS meeting in Vienna in 2010. Several other ideas for press releases are in the making, in conjunction with upcoming publications and meetings.

10. References
References appearing as: "name, XXX, T200x" are at: http://themis.ssl.berkeley.edu/publications.shtml
Other references:
Daughton et al., NM9.007; 2009APS.DPPNM9007D, 2009
Green, J. C. and M. G. Kivelson, JGR, 109, A03213, 2009
Mitchell et al., GRL, 17, 583-586, 1990.

Figure 9A. Mass media reports on THEMIS bespeak of the success of the science team the GSFC public affairs office and our capable Education and Public Outreach team in engaging the public in the excitement of space science.

Figure 9B. THEMIS is seen often in popular science magazines and the press.