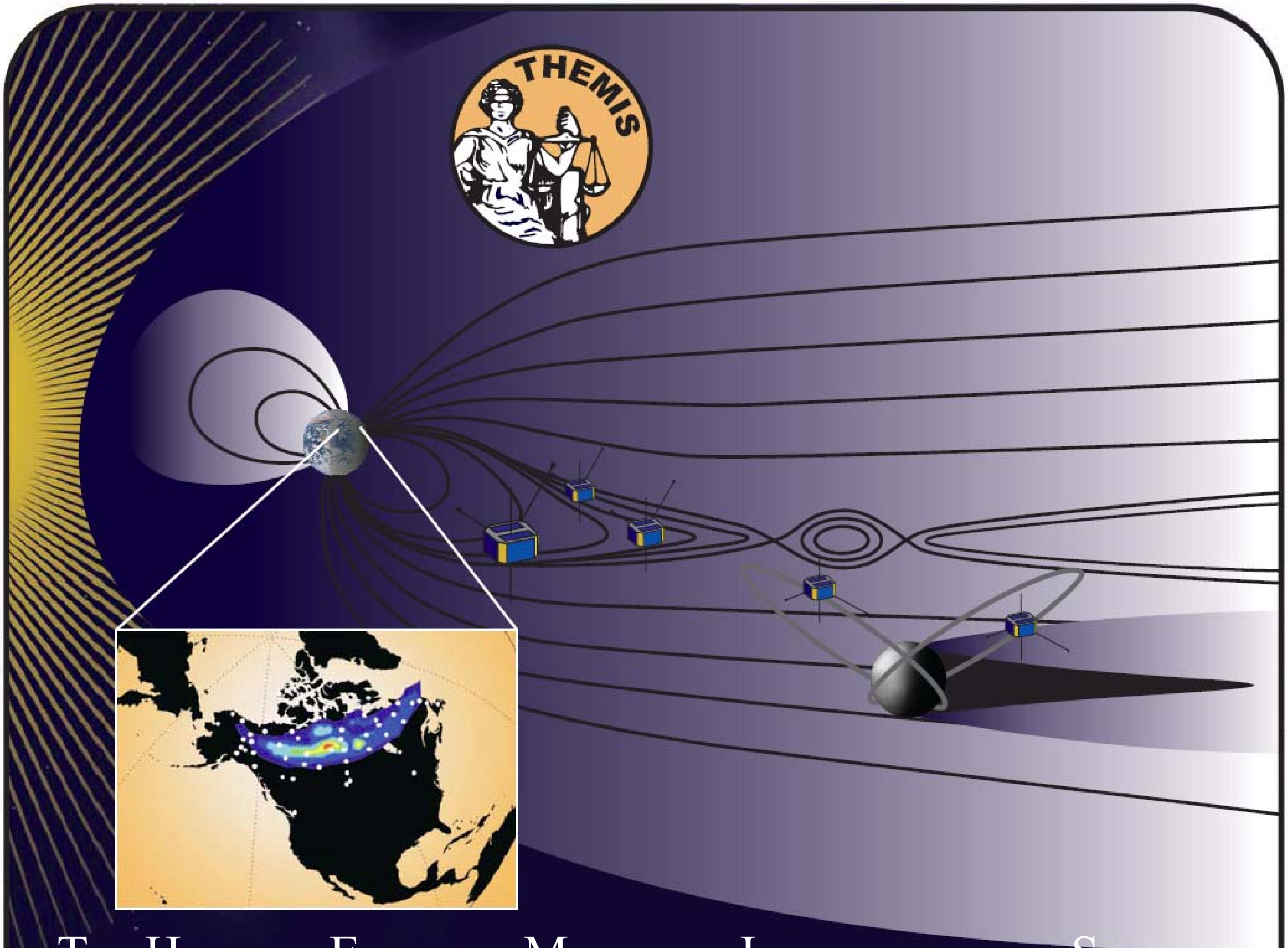
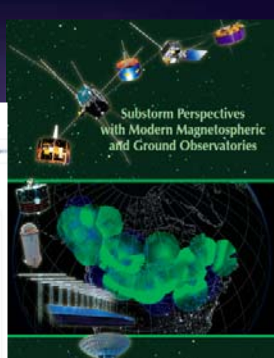


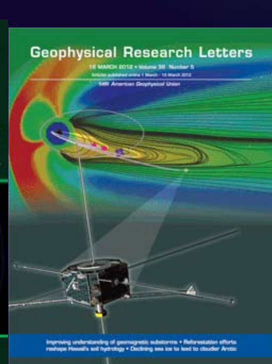
TIME HISTORY OF EVENTS AND MACROSCALE INTERACTIONS DURING SUBSTORMS: THEMIS

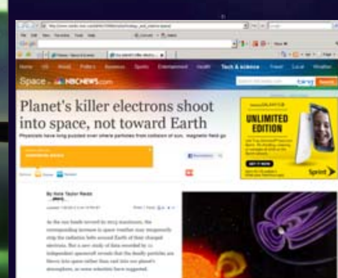
PROPOSAL SUBMITTED FOR:
SENIOR REVIEW 2013 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM
FOR THE
HELIOPHYSICS OPERATING MISSIONS
MARCH 08, 2013

V. Angelopoulos
THEMIS Principal Investigator
University of California

D. G. Sibeck
THEMIS Project Scientist
NASA/GSFC







TIME HISTORY OF EVENTS AND MACROSCALE INTERACTIONS DURING SUBSTORMS

PROPOSAL SUBMITTED FOR:
SENIOR REVIEW 2013 OF THE MISSION OPERATIONS AND DATA ANALYSIS PROGRAM
FOR THE HELIOPHYSICS OPERATING MISSIONS

Contents

1. Executive Summary

THEMIS, an efficiently developed and implemented five satellite constellation mission, was launched on February 17, 2007 as NASA's 5th MIDEX under $200M, a small fraction of the cost of missions with equivalent scope. After successfully completing its prime mission in 2010, THEMIS proposed and implemented a split into three Earth-orbiting (THEMIS "low") and two lunar orbiting (ARTEMIS) spacecraft groups to optimize its scientific return (Fig. 1A). Both missions have achieved many firsts, reshaping space science, answering longstanding questions regarding the origin of discrete and pulsating aurora, electromagnetic energy conversion in the magnetosphere, magnetic reconnection, upstream transients, the elusive origin of plasmaspheric hiss, the propagation and effects of morning chorus, the lunar wake and exosphere and many others. Science productivity is at an all-time high, with >130 refereed publications in 2012 alone (see http://themis.ssl.berkeley.edu/publications.shtml), and continues to rise thanks to: (i) a pro-active strategy to develop and distribute high-quality, high-resolution data products; (ii) the development and free dissemination of all-purpose analysis tools that enable optimal cross-mission Heliophysics System Observatory (HSO) data analysis; and (iii) strong THEMIS software and science team support for the research community. While 40% of the aforementioned papers were led by THEMIS team members and their partially-funded affiliates, the remaining 60% were led by non-THEMIS community members, showing evidence for heavy use of the data by the community at large. Moreover, 68% of all papers include THEMIS coIs or affiliates, showing the important in-kind support of the community by the THEMIS funded team. Finally, the analysis tools being developed by THEMIS can ingest data from dozens of other space and ground assets. "Plug-ins" for instruments on the Van Allen Probes and GOES spacecraft, >100 ground-based observatories, all SuperDarn sites, and the entire ERG mission exist, and plug-ins for MMS are under development. They represent a grass-roots science-community software developers' platform (herein referred to as: "SPace Environment Data System" or SPEDAS), that promises to become a space physics standard (like "solarsoft" for Solar Physics) and thus further optimize return from Heliophysics assets.

Today, THEMIS "low" and ARTEMIS (proposed jointly herein under their original name, THEMIS) boast a flawless operation, unscathed by space radiation and with all instruments effectively as good as new. With comprehensive, well-calibrated and -characterized space instrument suites in mint condition located at key equatorial vantage points at ~60R_E and inside ~15R_E, THEMIS herein proposes to use its significant remaining fuel resources and reconfigure, yet again, its orbits to simultaneously: (i) perform unique, cutting edge science that will revolutionize the field in its own right while (ii) optimally aligning itself with current and upcoming Heliophysics missions to usher in an era of unprecedented Heliophysics system science return per dollar.

Specifically, as its highest Prioritized Science Goal (PSG#1), THEMIS proposes to align the line of apsides of P3-P5 (Figure 1A) with that of MMS in FY14-FY16 to form a large-scale tetrahedron covering ion inertial to MHD lengths with P3-P4 in three vertices of that tetrahedron and MMS in the fourth. From these vantage points, the two missions will jointly study magnetopause and nightside reconnection, (a.k.a. "dipolarization") fronts, and injections while ARTEMIS provides pristine, high-fidelity solar wind data on the dayside or magnetotail flux content and reconnection locations on the nightside. This configuration will enable THEMIS to provide contextual information as well as explore ion physics (Hall current, density gradients, field asymmetries, pressure gradients and in/out-flows) while the four MMS spacecraft study electron kinetics at the dayside magnetopause and reconnection fronts or injections in the magnetotail. The use of SPEDAS plug-ins planned by MMS and facilitated by the THEMIS team promise optimal analysis of both mission datasets using one software platform. Nesting ion and electron scale tetrahedron configurations is not a new idea (see e.g., http://www.cross-scale.org) but would be exceedingly costly to implement as an entirely new mission.

When MMS increases its apogee to 23R_E in FY17 to FY18, THEMIS will increase the apogees of P3-P5 to 14-16R_E and enter into a resonant orbit strategy with MMS. The resulting frequent alignments along the magnetotail axis and the availability of THEMIS ground based cameras (MMS plans to be in the tail during winter) will result in an unprecedented opportunity for Heliophysics to unite its assets (ARTEMIS+MMS+THEMIS+Van Allen Probes+ others) and determine how kinetic phenomena (such as reconnection X-points, sharp gradients within reconnection fronts and injection-related radiation belt enhancements) result from and affect global changes. Similarly, while on the dayside, the spacecraft alignments will provide an unprecedented opportunity to study kinetic processes (such as foreshock bubbles, upstream waves, hot flow anomalies and the bow shock) and the resulting global magnetospheric responses (including energy coupling) to e. g. interplanetary shocks and sudden impulses. THEMIS proposes to enhance its high cadence "Fast Survey" data coverage as often as possible (up to 20hrs/day) to optimize joint event analysis with MMS and the Van Allen Probes during this unique period in our research field's history.

THEMIS proposes to perform this feat at a miniscule cost when compared to the system science returns it will provide, and at a small (20%) incremental cost to its baseline mission. THEMIS has already discussed this option with HQ as part of this Senior Review call. Maneuvers have already commenced under nominal funding in FY13 (many more are required) as this was critical for this opportunity to be made available to the community. An added benefit of our plan is that in the event of an inadvertent malfunction of one of the MMS satellites it enables THEMIS P3 to stand in its place with sufficient fuel margins. Albeit they provide lower time resolution observations in particle cadence mode, THEMIS wave measurements are quite capable of resolving electron microphysics.

THEMIS's PSG#2 applies in the event that THEMIS does not receive the OK to execute MMS alignments and HSO science optimization in the summer of 2013. Its goals are more modest and thus a subset of the goals of PSG#1. PSG#2 does not require the buildup of a differential precession of the line of apsides to match the MMS launch apsides nor any coordination with the MMS mission design team to ensure phasing between the satellites or data analysis systems. PSG#2 is thus independent of the MMS orbit (although fortuitous conjunctions with MMS will help if they occur). PSG#2 is the "baseline" THEMIS plan, motivated by recent findings regarding the efficacy of reconnection fronts (often called "dipolarization fronts") in converting 1-5x10^{15}J of lobe magnetic energy into plasma energy during their inward collapse from the reconnection X-point [Angelopoulos et al., 2013; submitted]. The fronts carry ~0.3MA of cross-tail current [Liu et al., T2012] and divert it into the aurora. After collapsing into the inner magnetosphere during substorm expansion or storm recovery phase the dipolar region expands tailward. THEMIS has shown that the interface between that dipole and tail-like region is the site of the quiet time arc [Sergeev et al., T2011; Jiang et al., T2012], and there is evidence this mapping may continue to occur during active times as the arc expands poleward and the dipole region expands outward well beyond 12R_E. Since the most intense energy release during a substorm occurs during the recovery phase it is important to understand how energy flows from lobe reconnection to the aurora through studies of this critical area. Moreover, it is important to understand how and why some (~20%) of the fronts result in geoeffective injections near geosynchronous altitude while many others do not [Sergeev et al., T2012]. One such geoeffective event rendered Galaxy 15 a "zombie" satellite for about one year on Apr. 5, 2010 [Connors et al, T2011]; it serves as a reminder that mid-tail phenomena can play a significant role in space weather and storm geoeffectiveness.

Towards PSG#2 we will use the tried-and-true strategy of resonant orbits as it we did during the prime mission, namely 1-2 R_E XY, XZ and YZ separations once each 4 or 8 orbits so that over the course of FY14-18 we will progressively explore the near-Earth region out to 16R_E. This is the region of the strongest cross-tail current diversion into the ionosphere, during the time of the largest substorm energy release, namely the recovery phase. On the dayside, it has now become clear that transient foreshock phenomena are important drivers for inner magnetospheric activity. On the dayside, THEMIS will explore the recently discovered foreshock bubbles (forming well beyond the bow shock), the process of hot flow anomaly and foreshock wave propagation through the magnetosheath and magnetosphere (in particular as a mechanism for driving ULF pulsations), the azimuthal evolution of boundary waves and the efficacy of Kelvin-Helmholtz waves at the flanks. In continued collaboration with the Van Allen Probes THEMIS will study how dayside and flank transients and magnetopause shadowing affect the sudden loss and acceleration of radiation belt and ring current particles. THEMIS does not depend on the Van Allen Probes as it can simultaneously measure both the inner magnetospheric phase space density and the solar wind/sheath/magnetopause drivers as well as nightside drivers (during 3 out 4, or 7 out of 8 orbits). However, it contributes to the synergy between Heliophysics missions such as BARREL and Van Allen Probes and international missions such as ERG by providing uniquely important information regarding the radial profiles of the equatorial phase space density out to large L-shells. Recent THEMIS discoveries [Turner et al., T2013] suggest that a combination of processes, including wave-acceleration, magnetopause shadowing, diffusion, and wave-scattering is responsible for storm geoeffectiveness; these processes can only be understood from a number of distributed HSO space and ground platforms. THEMIS will play a key role in this arsenal by providing not only 5 additional data points but the global magnetotail flux content and pristine energy input (ARTEMIS) and the source population for the radiation belts at large L-shells.

THEMIS notes with pain that the current 4-year guide was inadvertently reduced due to a clerical error that NASA/HQ has confirmed (see Section 4.2) but requested that a THEMIS proposal still be submitted with the intent to fix the problem after this Senior Review. THEMIS's contract extension options, already negotiated, reflect the proposed "baseline" plan, not the guide, which is encouraging. We are however compelled to explain that should the guide be implemented, the funding loss would represent a severe toll to the scientific productivity of the field: a >45% reduction in community-wide THEMIS-related science; a >66% decrease in THEMIS-led science, significant attrition of students and young researchers and a dramatic loss of potential for HSO science.

THEMIS's results were featured on National Geographic, NBC news and other popular media programs/articles related to the discovery of what causes the pulsating aurora (Nishimura et al., Science, T2010) and what causes the great escape of electrons from the radiation belts (Turner et al., Nature Phys., T2012); 5 JGR/GRL Editor's highlights; a GRL cover; 2 books (a JGR special issue on substorms, an AGU monograph on auroral processes and a Space Science Review book on ARTEMIS, in press) and 5 NASA press releases generating media attention with audiences of millions. The The discoveries highlighted in the above press releases and the forthcoming goals of the THEMIS mission are directly aligned with the objectives and focus areas of the 2010 SMD Science plan. We seek to understand the fundamental processes that occur in the space environment; to determine how planetary habitability is affected by solar variability and to provide the knowledge needed to improve space weather forecasting. For example THEMIS targets understanding energy transformation, energy partitioning and transport at reconnection fronts, particle acceleration upstream at foreshock bubbles, and phase space density evolution in the inner magnetosphere due to wave-particle interactions, all of which are ubiquitous across planetary space environments and at the Sun, yet have tremendous importance for space weather understanding and prediction. Finally, THEMIS is completely aligned with the recommendation of the Heliophysics Decadal Survey to enable and optimize a powerful HSO. In fact, THEMIS lies at the heart of such a Heliophysics Division response to this recommendation as it provides a flexible means of enabling NASA/HQ to align and link its current and future assets and provides the most comprehensive and truly global coordinated study of our space environment while addressing the field's most pressing questions.

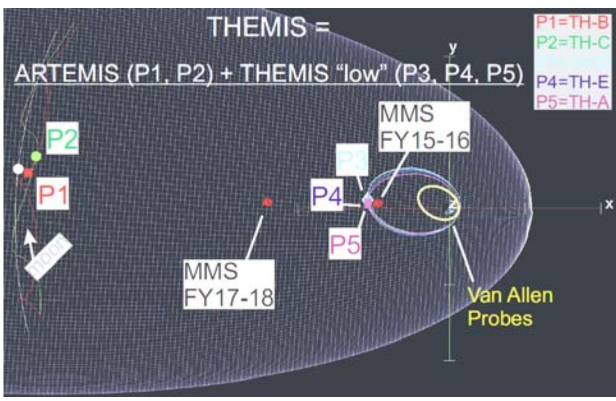


Figure 1A. THEMIS mission with its constituents: THEMIS "low" P3-P5 and ARTEMIS P1 and P2, shown for 2012-07-03 but also depicted as they can be in 2015-16 along with MMS. MMS's electron scale tetrahedron in 2015-16 can reside in a larger scale tetrahedron formed by THEMIS' P3-P5 and MMS; ARTEMIS measures global lobe flux release and reconnection sites and Van Allen Probes studies their effects for the inner magnetosphere. In FY17-18 THEMIS apogees will be raised further (13-16R_E) to create resonant orbits with MMS (not shown). THEMIS's proposed alignment with MMS unites HPS assets into a powerful system-observatory.

2. Recent discoveries shaping the future

Over the last three years THEMIS "low" and ARTEMIS have conducted significant discoveries that have changed our understanding of how the magnetosphere and its coupling to the solar wind and ionosphere take place. These pave the wave for reshaping both THEMIS's plans and have even greater significance for the observational strategies that ought to be employed by MMS and inner magnetospheric missions. They reinforce the view expressed in the HPS Decadal Survey that implementation of an HSO is the best way forward for Heliophysics. This section describes the findings that affect THEMIS's proposed science planning.

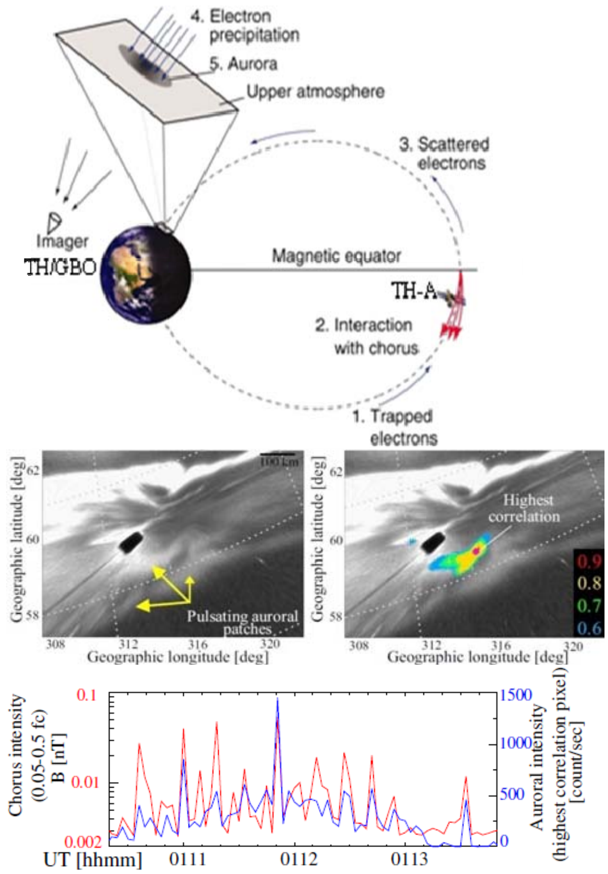


Figure 2A: New mapping tools using whistler waves and patchy aurorae enable studies of active time arcs which likely map to nightside distances >12R_E and sites of major electromagnetic power conversion.[Nishimura et al., T2010]

2.1 Magnetotail

By 2010 it had been realized that transient magnetotail activations (flow bursts, busty bulk flows – BBFs-associated with dipolarization fronts) move from the reconnection site all the way to the inner magnetosphere. These harbingers of tail reconnection take part in all phases of a substorm (including - in fact initiating – expansion phase onset) and even during the few minor storms encountered during the solar minimum of the first years of THEMIS. However, mapping remained an open question. Are the quiet arcs close enough to Earth that they overlap with the radiation belts, or is mapping so severely distorted by strong growth phase currents that these arcs map to the mid-tail regions? We are happy to report that thanks to the

THEMIS space and ground observatories this issue has been closed by consensus (in the THEMIS-dominated Substorm Focus Group of the Geospace Environmental Modeling meeting in 2011): The quiet arcs map to the interface between the dipole and tail-like field lines, near the inner edge of the electron plasma sheet [Sergeev et al., T2011; Jiang et al., T2012].

Therefore earlier observations by Nishimura et al., [T2010] that the pre-onset arc is perturbed/activated by North-South arcs emanating near the polar cap boundary during substorm onset, are indeed consistent with the idea that reconnection flows result in the inrush of plasma and magnetic flux as close as the inner edge of the plasma sheet (located at distances of 8-10R_E in the events under study). As the newly reconnected plasma piles up new magnetic flux against the strong magnetic field of the inner magnetosphere the dipole expands and engulfs the satellite, quenching the flow locally (a spatial aliasing effect) both tailward and azimuthally. The resultant expansion of the plasma sheet may be associated with the poleward and azimuthal expansion of the aurora; suggesting again that the new dipole-tail like boundary is the new location for the active arcs. This makes the region tailward of 10R_E a prime candidate for studies of current diversion and energy dissipation/conversion. Since substorm late expansion and early recovery phase is the time when most energy is deposited in the aurora and the inner magnetosphere, we have to look to such distances to determine global energy transfer from magnetic reconnection to the auroral ionosphere.

Mapping has seen one more important advance in the THEMIS era (Fig. 2A): Nishimura et al., T2010 carefully cross-correlated whistler wave emissions on THEMIS spacecraft at ~10R_E and pulsating aurora patches seen by the THEMIS ground cameras to identify (through the peak correlation) the location of the spacecraft's magnetic footprint to within 100km in the ionosphere. These techniques make validation of magnetic mapping by modified Tsyganenko-type models possible, since patchy aurorae are typical at such times and can be used to better understand the locations of active time (late-growth, early recovery time) arcs and energy flow into the ionosphere.

But what dictates the inward stopping point of a dipolarization front? Apparently, as Sergeev et al., T2012 found, this is a combination of stresses of the inner magnetosphere and the density (more strictly the entropy) of the recently reconnected flux tube. In a JGR Editor's highlight study of multiple incoming dipolarization fronts (Fig. 2B), they showed that the parameter that best predicts the innermost penetration distance of a flow burst associated with a density depleted bubble is indeed the volume-integrated flux-tube entropy. Trans-geosynchronous injections (outside geosynchronous distance) are quite common and have properties (including drifts and dispersion) that are similar to those at geosynchronous (Gabrielse et al., T2012). One obvious way of increasing flux tube entropy is to dipolarize the field, which is what happens near expansion phase onset. Thus it is evident why flow bursts cannot penetrate closer in at times of late substorm expansion and why studies at further distances of energy transport are important to understand the dominant energy dissipation at active times.

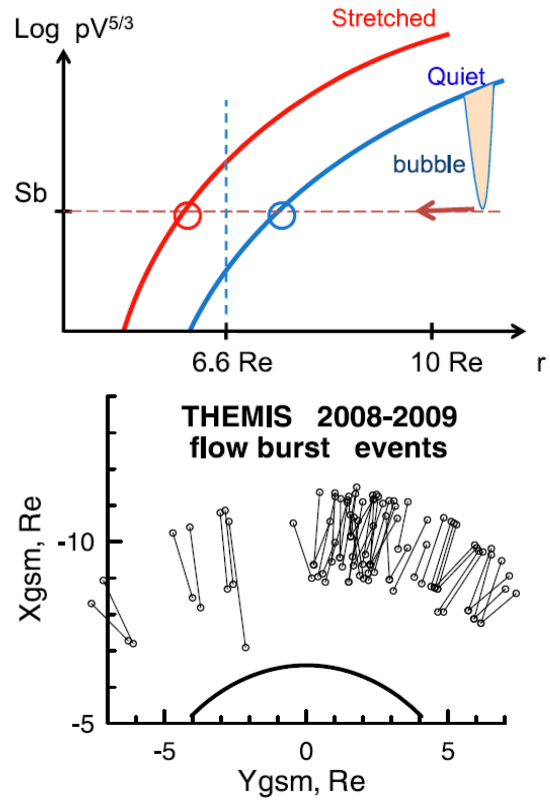


Figure 2B: Sergeev et al., [T2012] showed that the innermost penetration of a flow burst depends on the burst's entropy and the radial profile of the entropy in the inner magnetosphere. Most bursts (80%) do not reach geosynchronous altitude; this makes geosynchronous injections poor indicators of substorm activity.

One other aspect of the transient dipolarization fronts is their current system. In a comprehensive statistical study, Liu et al., [T2012] demonstrated that this current system is saddle-like, and current flow lines that diverge from purely parallel to the equator (i.e., from a purely perpendicular current system) as an observer moves away from the neutral sheet. The total current, ~0.3MA on average, is thus diverted away from the equator, along the field lines in a Region-1 sense. A smaller Region-2 sense current system exists slightly earthward, likely due to pressure gradients. Just such a double Region-1/Region-2 pair has been observed in a recent refinement of the standard substorm current wedge when inferred from multiple spacecraft observations (Sergeev et al., 2013, submitted). Thus the Liu et al., observations suggest that the (typically 0.5-1MA) global substorm current system is built up by individual wedgelets. But at what point in the life of a dipolarization front does the current diversion into the ionosphere start? Is that a consequence of the burst interaction with the inner magnetosphere, or an inherent property of front propagation? This is important to understand as it pertains to both the effect of the ionosphere on flow burst propagation and the energy dissipation as recently reconnected flux bundle shrink inwards towards the inner magnetosphere. Multi-spacecraft studies of the undersampled regions beyond $12R_E$ are required to answer this important question related to power dissipation and electromagnetic energy coupling during substorms.

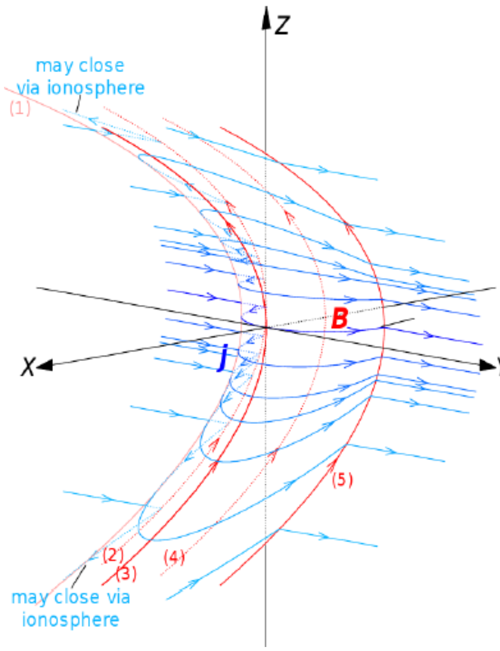


Figure 2C: Liu et al., [T2012] determined the saddle-shaped current system of an approaching dipolarization front, showed its typical magnitude to be ~0.3MA and its dominant system to have a Region-2 sense.

At the mid-tail plasma sheet, it has been amply demonstrated that reconnection participates at the early stages of substorm onset. Ground observations, however, continue to befuddle us on this issue. Combined radar and THEMIS all sky imager observations suggest that polar cap patches and flows converge towards the PBI meridian at during poleward boundary intensifications. The polar cap flow is striated and one of the polar cap flow channels seems to abut the location of the PBI at the time of its first brightening. Is this an indication of lobe channels of cold plasma initiating mid-tail reconnection? Or does closed plasma sheet reconnection start first?

Luckily the ARTEMIS spacecraft pair can provide significant new information on this topic and, if aligned with MMS, they can completely resolve such questions. ARTEMIS has already observed hundreds of plasmoids

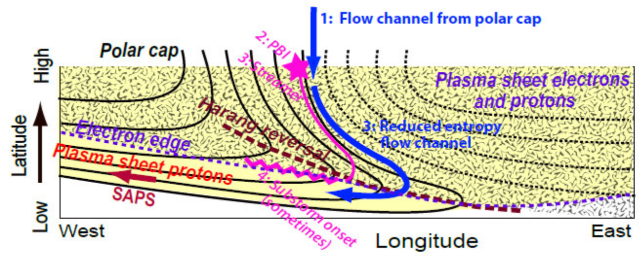


Figure 2D: In this Editor's highlight paper, Lyons et al. [T2012] suggested that polar cap flows initiate tail reconnection that eventually leads to substorm onset. Only multi-point observations (MMS, ARTEMIS or both) can resolve whether tail reconnection is initiated by external (cold lobe plasma) forcing or is spontaneous. ARTEMIS has already started to make significant contributions along these lines.

that are being studied statistically in a correlative fashion from its two vantage points. Case studies (Fig. 2E) show that plasmoids are localized to ~ a few R_E. This localization may, in fact, be responsible for why they are observed to emerge and grow out of the plasma sheet, without evidence for lobe reconnection [Li et al., T2013].

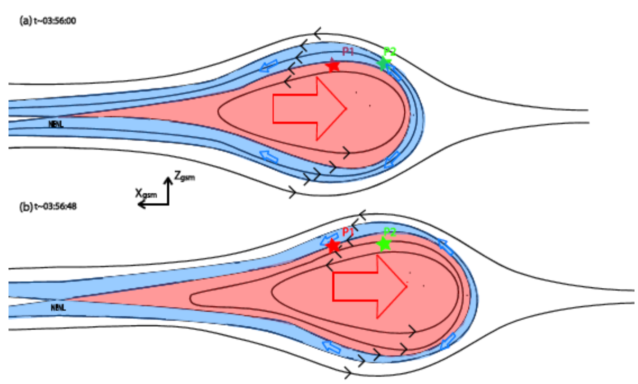


Figure 2E: Li et al., [T2013] find that plasmoid expulsion takes place thanks to plasma sheet reconnection, but without lobe reconnection. Only multi-point observations (MMS, ARTEMIS or both) can resolve whether lobe reconnection is initiated by external (lobe plasma) forcing, or if it is spontaneous. ARTEMIS has already started to make significant strides along these lines.

In fact it is likely that lobe reconnection only happens at late substorm expansion, and never at substorm onset – suggesting that the initial plasmoid that forms can only be released if it is localized enough to grow and slip through the plasma sheet field lines. This would mean that significant energy release during substorms does not really take place in all earnest until much after the first one or more plasmoids have been released.

The 2012 THEMIS (low) - ARTEMIS conjunctions, in fact, indicate exactly that (Angelopoulos et al., 2013, submitted): Fig. 2F shows that the integrated solar wind electric field (red), a proxy of flux entry into the lobes, is constantly increasing during the 3 hours of the event in question, as the solar wind Bz was negative at the time. The measurements of total pressure at ARTEMIS enable us to compute the local flaring angle from magnetopause pressure balance. Using the standard Petrinec and Russell [1996] functional form for the dependence of the flaring angle on distance as well as tabulated values at the terminator, we can then determine the tail radius and from that the total lobe flux (black). The difference is the lobe flux transportation by tail reconnection. It is evident that 0.5GWb were transported during this event. Both earthward and tailward flux transport were measured during the bursty flows and plasmoid passage. Spacecraft P3 and P2 are in the positions shown in Fig. 1A, on opposite sides of the reconnection point. The power conversion rate in the earthward dipolarization front at P3 as well as at the tailward negative B_z front observed at P2 was very significant in both cases (Fig 2F, bottom). These fronts, emanating from the reconnection site are called "reconnection" fronts. When power conversion at these fronts was integrated over temporal and spatial scales commensurate with the observed flux transport duration and extent we find that it is sufficient to account for the total energy conversion expected from the lobe magnetic energy reduction. That is about $3x10^{15}$J, i.e., about equal to the amount of energy dissipation during a substorm.

This means that power conversion reconnection fronts are very significant on global scales, even those known to be kinetic on ion [Sergeev et al., T2009; Runov et al., T2010, T2011] and electron scales [Zhang et al., T2011]. These are the sites where lobe energy dissipation operates as flux tubes shrink, moving away from the reconnection point! They are even more important than the reconnection X-point itself, since they are responsible for the first step in the energy release from lobe magnetic energy to eventual ionospheric heating and Van Allen belt ion and electron heating, or plasmoids. They require further multipoint studies at the location where they evolve unaffected by any interaction with the inner magnetosphere, outside of X~-$10R_E$, yet where the cross-tail current is the most intense, inside of ~ $16R_E$. Understanding the distribution of the converted power into kinetic, thermal, motional energy of the plasma, or waves; and the coupling of that energy to the inner magnetosphere and ionosphere is the next most important thing for understanding tail dynamics in the next few years.

In summary, we know from recent observations that the region between 10-$16R_E$ harbors intense electric fields, flows and currents that couple to the auroral ionosphere and inner magnetosphere. This region is under-explored because THEMIS has not used its full multipoint observational capability outside of $12R_E$ and Cluster has not spend much time in this region (being polar-orbiting and high-apogee). *THEMIS's planned apogee increase of P3-P5 in the next 5 years will provide the much needed data, tools and personnel to study the intense power conversion region of 10-16R_E in the nightside equatorial magnetosphere. Moreover, it is critically important to understand the coupling of that region to the reconnection sites (with the help of ARTEMIS, Geotail and allied MMS measurements), to the inner magnetosphere (with the help of inter-THEMIS correlations, P3-P5, GOES, and Van Allen Probes) and to the aurora (with the help of THEMIS ground based assets, and allied observatories, such as magnetometer arrays, SuperDarn and other radars).*

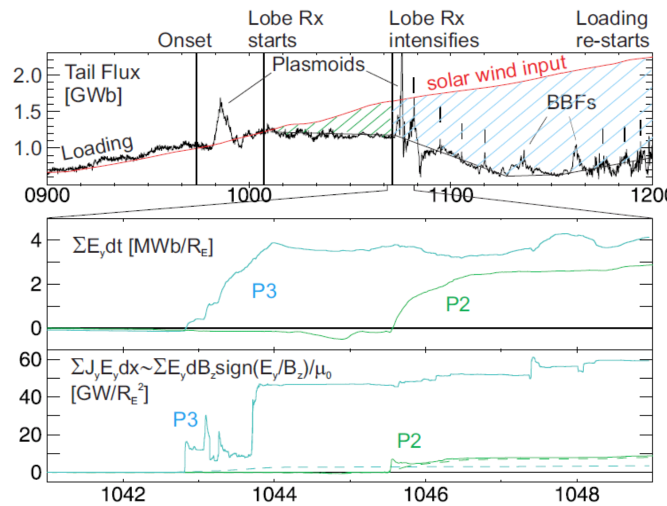


*Figure 2F: Top: red curve is flux transport into the tail from the solar wind, estimated by cumulative integration of the merging electric field from OMNI data; black curve is the observed tail lobe flux, estimated by determining the tail flaring angle and tail radius from pressure balance at ARTEMIS P2.The difference, highlighted, is the amount of flux the tail has lost to nightside reconnection. Tail reconnection is most intense after 10:41UT and for 30 minutes. Middle: the cumulative integrated flux transport is most intense during bursty flows accompanied by "reconnection fronts" at P3. Bottom: the cumulative integrated J*E, the power conversion density, in units of GW/R_E^3.*

2.2 Dayside

By 2010 it had been realized that transient dayside phenomena (hot flow anomalies, or HFAs, upstream waves, pressure pulses and transient reconnection) apply significant pressure variations to the dayside magnetosphere and have global consequences. Today, after recognizing the importance of a previously unknown phenomenon, foreshock bubbles, and solidifying the importance of the others for energy coupling into the inner magnetosphere, we recognize the importance of studying these phenomena in-situ, at the place of their generation, but also in conjunction with other measurements in the pristine solar wind, the inner magnetosphere, and the ground, to fully assess their global consequences.

foreshock bubbles may have gone unrecognized as HFAs because the two share similar characteristics (Fig. 2H).

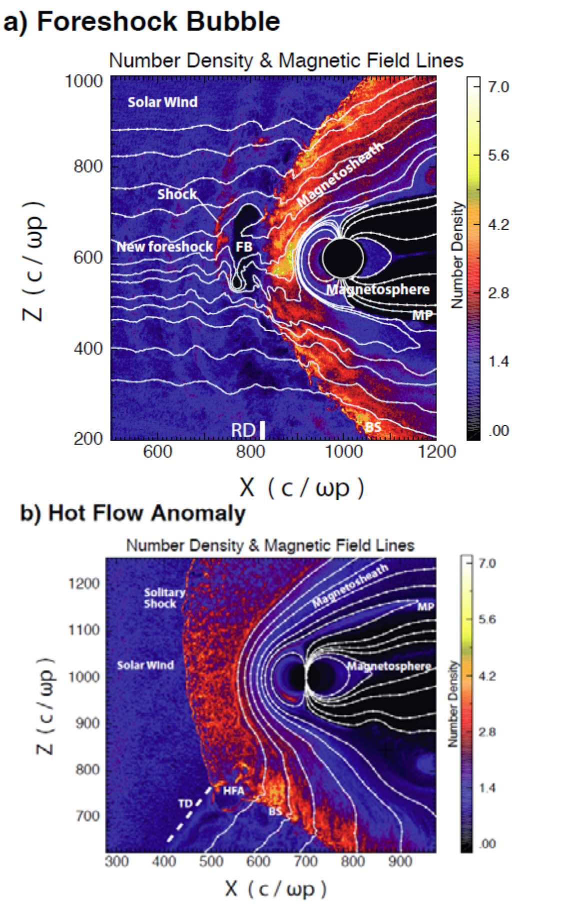


Figure 2G: Foreshock bubbles in hybrid simulations (top) contrasted with the more traditional (and smaller) hot flow anomalies (bottom). Note that HFAs form close to the shock and are convected by it, whereas foreshock bubbles form in the solar wind upstream of the shock and are convected by the solar wind. Equatorial measurements from beyond the shock distance (as planned by the extended THEMIS phase) are needed to study these kinetic phenomena in their birthplace, but also in conjunction with other ARTEMIS, THEMIS and allied HSO measurements in the pristine solar wind, the inner magnetosphere and on the ground. From Turner et al., [T2013].

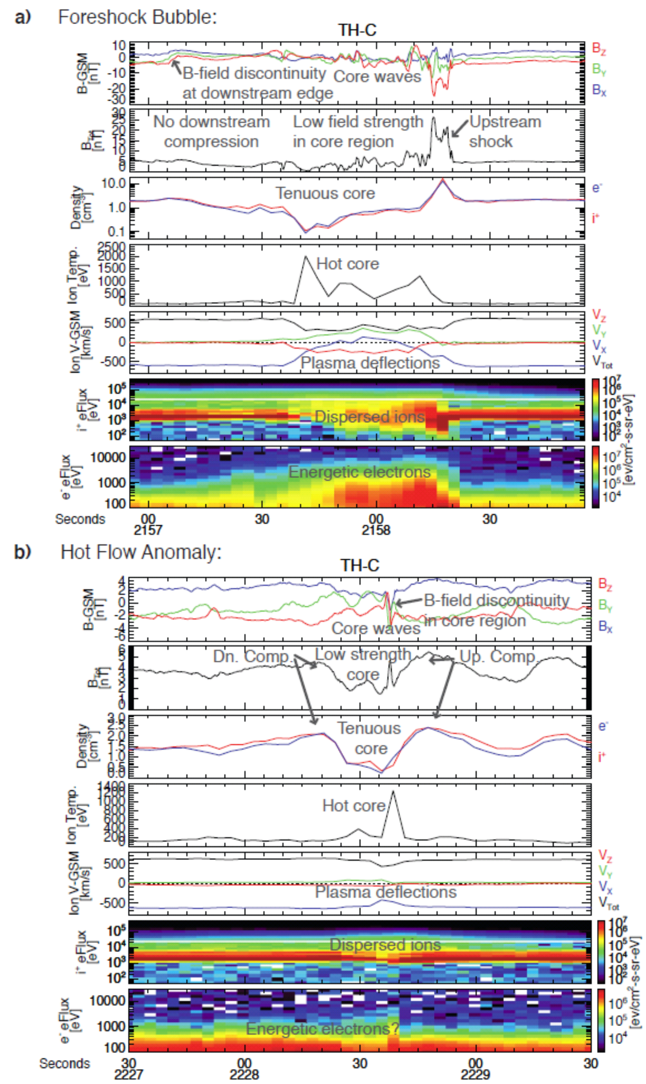


Figure 2H: Foreshock bubble at ARTEMIS P2 (TH-C) (top) contrasted with the more traditional HFA seen at another time on the same spacecraft (bottom). From Turner et al., [T2013].

The new phenomenon, foreshock bubbles, compared and contrasted to the previously known hot flow anomalies in simulations in Fig 2G and in data in Fig 2H, is ubiquitous at plasma-shock interactions when rotational discontinuities move through low cone angle magnetic fields upstream from the shock. Reflected particles become entrapped upstream of the discontinuity resulting in extremely large, high pressure cavities that are able to accelerate particles locally, through Fermi acceleration, as well as grow in time as they approach the shock. Reported initially in hybrid simulations by Omidi et al. [2010] the bubbles have now been found not only to exist but also to be very common in THEMIS and ARTEMIS solar wind observations [Turner et al., T2013]. Previously observed foreshock bubbles may have gone unrecognized as HFAs because the two share similar characteristics (Fig. 2H).

The extreme variations in the upstream region have global consequences. Multipoint THEMIS measurements and a comparison with hybrid code simulations enabled Korotova et al. (2012) to demonstrate that simple tangential discontinuities can simultaneously launch outward bow shock undulations and powerful inward propagating pressure fronts that cross the magnetosheath to generate signatures throughout the inner magnetosphere, as shown in Fig. 2I (where the letters B, C, D, E, and A refer to THEMIS spacecraft P1-5).

In fact, Hartinger et al., [T2012] recently showed that such transient ion foreshock phenomena not only generate pressure pulses but also routinely drive global magnetospheric Pc5 ULF waves with E and B field amplitudes up to 10mV/m and 10nT near geosynchronous orbit (Fig 2J). Similar behavior is seen when HFAs and other transients impact the magnetosphere, but FBs elicit the largest response. The local time sector of peak magnetospheric response correlates well with the location of the ion foreshock. Case and statistical studies, simulations and theory now suggest that transient foreshock phenomena play an important role in driving ultra-low frequency (ULF) activity in the magnetosphere. Such activity couples effectively not only to field line resonances and hence dumps energy directly to the ionosphere, but is also known to accelerate radiation belt particles in the aftermath of corotating interaction regions.

Understanding the processes that generate these foreshock kinetic phenomena and their coupling to the magnetospheric requires the appropriately equipped, positioned, and spaced spacecraft that THEMIS plans to have in place during the next 5 years. This is particularly important during the forthcoming solar max and declining phase of the solar cycle, when corotating interaction regions are most prevalent in the solar wind.

Finally, THEMIS studies near the subsolar magnetopause provide important new information. Their magnetic reconnection is often transient, with repetition cycles on the order of 5-10 minutes, but can also continue steadily for hours, under low plasma beta (β) conditions. Until recently what controlled the rate and stability of reconnection upstream has been a puzzle.

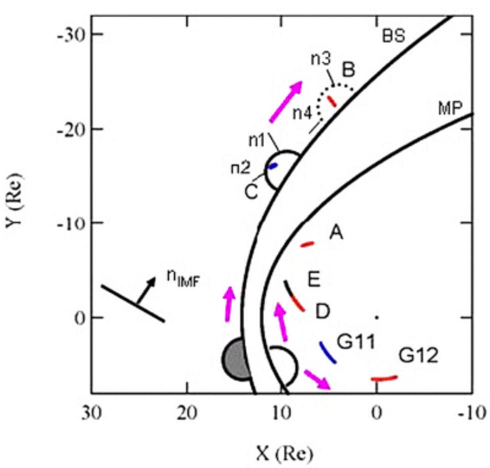


Figure 2I: Extreme shock variations are recorded on THEMIS during an upstream event; it was seen as a pressure pulse penetrating the dayside magnetosphere Korotova et al., [T2012].

Swisdak et al. [2010] recently reported that reconnection is suppressed when the jump in β across the magnetopause, Δβ, satisfies the relationship: $\Delta\beta > 2\ (L/\lambda_i)\ \tan(\theta/2)$, where θ is the magnetic shear, L the gradient scale, and λ_i ion debye length across/inside the current layer. The THEMIS team immediately set out to check this prediction. The statistical study of THEMIS magnetopause crossings shown in the lower panel of Fig. 2K indicates that non-reconnection crossings occur for low shears and large jumps in β across the magnetopause. Furthermore, the upper panel indicates that reconnection occurs over a larger range of shears for low than high Δβ (Phan et al., T2012). Thus our results provide striking confirmation of the Swisdak et al., [2010] model.

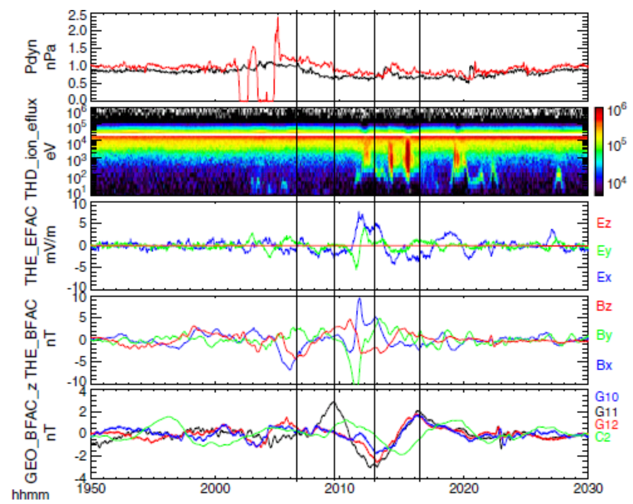


Figure 2J: Transient foreshock phenomena drive significant ULF activity in the inner magnetosphere. Top panel shows data from TH-B (in the solar wind, black) and THC (in the ion foreshock, red) during the passage of a foreshock bubble. The response in the inner magnetosphere (bottom 4 panels) is prolonged and dramatic, with significant power in Pc5 waves [Hartinger et al., T2012]. The ULF waves can accelerate radiation belt particles during stream-stream interactions regions and storms in general. From careful and systematic global studies of these kinetic transient phenomena we stand to gain significant knowledge regarding solar wind-magnetosphere coupling. Such studies require the presence of spacecraft directly upstream of the shock (THEMIS extended phase) and pristine, high-fidelity solar wind monitors (such as ARTEMIS).

The suppression of low-shear reconnection at high Δβ (and therefore high magnetosheath β) has general consequences for the occurrence of reconnection in space and laboratory plasmas. It is very likely that this effect explains why most prolonged magnetopause reconnection events have been observed for low magnetosheath β. Under such conditions the magnetosheath plasma is stable to the mirror-mode, allowing relatively steady β conditions in the sheath, and allowing magnetopause reconnection to be steady. Similarly, bursty reconnection is expected when the underlying magnetosheath β is high and mirror waves are present, producing fluctuating intervals of low and high-β. At the magnetopause flanks, however the data are far more complex and do not follow the aforementioned simple β–shear relation. It seems likely that flow shear also affects the rate and duration of reconnection. Moreover, as Kelvin-Helmholtz waves are expected to form in that region, reconnection sites within rolled up vortices at the terminator and further downstream may start to form. Further testing of these hypotheses requires multi-spacecraft observations to simultaneously examine β in the magnetosheath and flow shears across the boundary while observing the onset and rate of reconnection at the magnetopause.

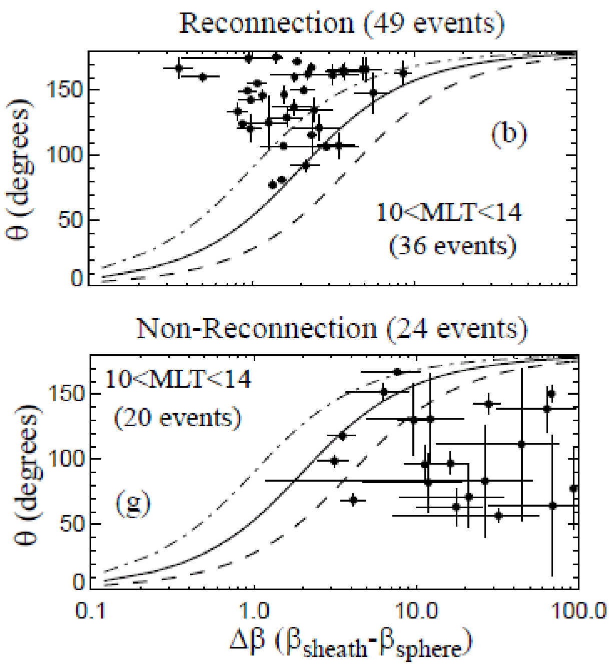


Figure 2K: Testing the Δβ-shear relation of Swisdak et al [2010], Phan et al., [T2012] using THEMIS data showed that reconnection is suppressed under high Δβ.It is unclear if these observations are valid in the presence of flow shear near the flank magnetopause. Further multi-point tests of this relation at the magnetopause, and the conditions for reconnection at the flanks await multipoint observations by THEMIS in FY14-18.

THEMIS plans observations at distances out to $16R_E$ that will test the leading hypotheses for magnetopause reconnection and extend them to observations under cases of flow shear near the terminator and flanks of the magnetopause. The nested THEMIS-MMS ion and electron scale tetrahedra will revolutionize our understanding of reconnection phenomena at the dayside magnetopause and other space plasma environments.

2.3 Inner magnetosphere

Since 2010, THEMIS studies have advanced our understanding of wave generation, properties, and wave-particle interactions in the inner magnetosphere.

With increasing solar activity, THEMIS has now captured more than 50 storms from the multipoint perspective that enables Heliophysicists to appreciate their relative importance and inter-dependence. Consistent with reports from previous solar cycles and more spatially-constrained databases, we find that 58% of geomagnetic storms result in enhanced peaks in electron radial phase space density (PSD), 19% resulted in depleted peaks, and 23% resulted in no significant change PSD peaks [Turner et al., T2013]. This extends previous results from geosynchronous altitudes out to $12R_E$, and confirms the maxim that "not all storms are created equal" at least in terms of their geoeffectiveness. Moreover, by studying individual storms that epitomize such disparate electron PSD behaviors during otherwise similar Dst and Auroral Electrojet (AE) profiles, THEMIS has been able to show the following: 1) growing peaks in PSD were colocated with chorus waves observed outside the plasmapause during active periods of the PSD-enhancing storms, but not during the PSD-reducing storms, providing good evidence for the critical role of the wave acceleration mechanism during PSD-enhancing storms; 2) outer belt dropouts due to magnetopause shadowing and subsequent outward radial transport were a key loss process during all storms; 3) a slow decay in PSD is often associated with hiss; 4) precipitation loss caused by wave-particle interactions with EMIC waves was important during the PSD-depleting storms but not the PSD-enhancing storms; and 5) ULF-wave driven radial diffusion away from peaks in PSD was evident during the recovery phase of the PSD-enhancing storms and therefore enhanced ULF wave power is critical in the redistribution of the PSD after local acceleration. Moreover, recent combined studies with Van Allen Probes showcase the importance of nightside injections in creating the whistlers and EMIC waves that partake in storm time PSD enhancements and losses, and also pre-accelerate electrons to significant intermediate energies (100keV) prior to injection into the inner magnetosphere, enabling wave-particle interactions there to further accelerate them to relativistic energies.

It is evident that a variety of waves, and particle acceleration/loss processes that had been studied individually in the past conspire to accelerate particles during one type of storm, but flux depletion in others, depending on the external drivers. These results strongly suggest that a system-observatory approach is required to make progress in inner magnetospheric research. THEMIS's planned large inter-spacecraft separations in FY14 (8-8-8 hrs along-track) are ideal to sample storms from a maximal spread in positions when combined with the Van Allen Probes and GOES datasets.

THEMIS separations will remain at 2-4-18 hours along track throughout FY13 (Fig. 2L), providing significant opportunities for joint studies with other spacecraft, such as during the recent October 2012 storm. This is true especially with data analysis tools such as SPEDAS (Fig. 2L). The particular storm under study was a "double-dip" storm where the second dip resulted in significant electron acceleration. The statistical study of substorm electron injections reported by Gabrielse et al. (2012) needs to be parameterized as function of internal and external drivers and folded into a statistical picture of sources, complementing THEMIS in situ measurements of the trans-geosynchronous nightside source region.

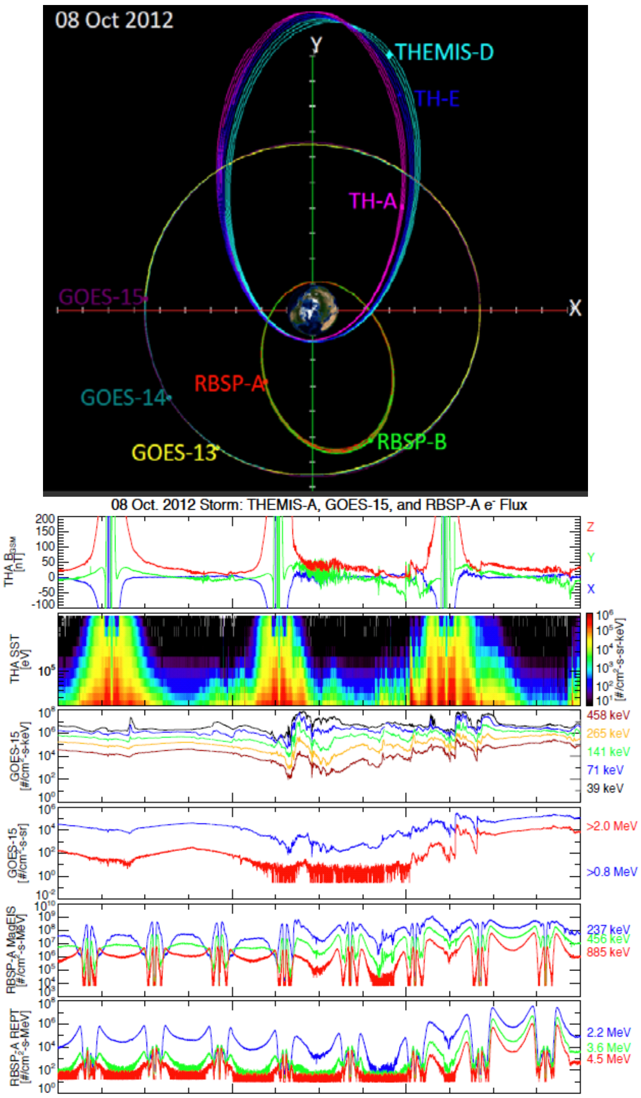


Figure 2L: Working in conjunction with the Van Allen Probes, GOES, ground based assets and upstream monitors, THEMIS provides the precise observations that our field needs to tackle the complex problem of storm geoeffectiveness. THEMIS observations of high L-shell sources, PSDs, losses and waves represent a once-in-a-lifetime opportunity for an advanced HSO. Tools developed by THEMIS but adapted for joint analysis (SPEDAS, used for plotting the bottom panels and for analysis) make scientific collaborations far more efficient and powerful.

During the last three years, the THEMIS team has finalized its characterization of the solid state telescopes response to energetic particle fluxes. Thanks to the full use of anticoindicence detectors, penetrating electrons no longer affect the calibrated data up to 1MeV and penetrating ions remain a problem only in the inner belt. GEANT modeling and inter-anode and inter-spacecraft calibration of detectors have also improved our understanding of the final energy calibration and dead-layer response. Clean particle fluxes are now available routinely throughout the entire mission in the outer radiation belt. This work made possible to demonstrate that peaks in the profiles of electron PSD versus radial distance result from wave-particle interactions [e.g., Turner et al., T2012] and pitch angle variations in injected particle arrival times.

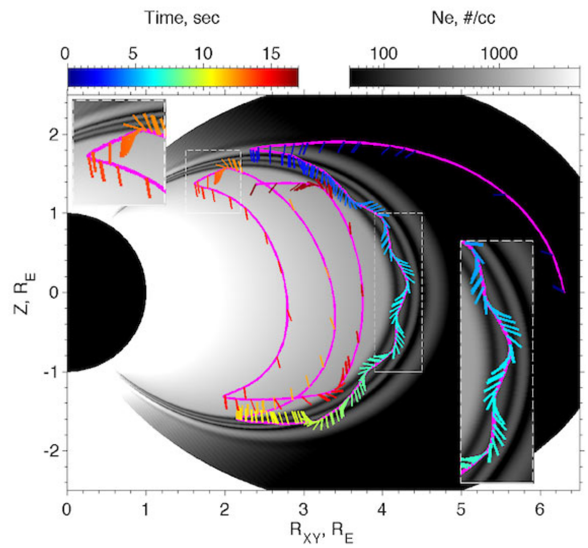


Figure 2M: A representative chorus ray guided by a density crest leaking into the plasmasphere to amplify hiss waves there. The magenta line is the ray path along which wave normal directions are denoted by the short segments color-coded according to propagation time (up to 17 seconds). The model plasma density is shown in the background in gray scale.

Finally, very significant progress has been made in understanding wave generation, properties, and propagation, such that these can feed into global diffusion models and reanalysis tools. For example the azimuthal propagation properties of chorus in the inner magnetosphere have recently been revealed [Li et al., T2013]. Moreover, the amplitude of the hiss waves derived from ray-tracing chorus waves leaking into the plasmasphere has been quantified in a JGR Editor's pick by Chen et al. [T2012]. Hiss waves are a provide a major loss mechanism for relativistic electrons. These studies promise a future in which we can model hiss amplitudes as a function of chorus amplitude, which can in turn be modeled as a function of nightside injection rate and plasma properties. In combination with other HSO assets, THEMIS correlative studies from multiple vantage points out to L>12R_E will advance our understanding of inner magnetosphere particle acceleration and loss. Specifically, *THEMIS is unique amongst all HSO assets in continuing to provide radial space density information out to large distances in the forthcoming peak and declining phase of the solar cycle. On the nightside, THEMIS will measure the injections that drive chorus, EMIC, and hiss wave growth in situ, while on the dayside it will measure the ion foreshock transients and upstream waves that power electron flux-enhancing ULF waves and the sudden dynamic pressure enhancements that compress the magnetosphere and thereby enable rapid magnetopause shadowing of inner magnetosphere fluxes.*

3. Science plan

Recent THEMIS/ARTEMIS discoveries reinforce the view expressed in the HPS Decadal Survey that implementation of an HSO is the best way forward for the field of Heliophysics. In this section we describe the science plan for accomplishing an optimal (PSG#1), baseline (PSG#2) and a scientifically severely decimated THEMIS implementation under the present guide.

As spelled out in the 2010 SMD science plan, the primary goals of the Heliophysics (HPS) Division are to understand the fundamental processes of our space environment that determine planetary habitability and space weather effects due to solar variability. The field of space physics is at a crossroads: First, scientifically, it is now understood that kinetic processes in the magnetotail, on the dayside and in the inner magnetosphere have global (system-wide) consequences for energy coupling and dissipation. Second, an unparalleled opportunity to coordinate current and upcoming multi-spacecraft missions during the active and most interesting phase of a solar cycle is emerging. Arguably the potential for discovery by NASA's heliophysics spacecraft will be greater during the next 5 years than ever again. The ability of THEMIS and ARTEMIS to adjust their orbits and optimally combine HPS's assets can be at the heart of the HPS Division's response to the call by the HPS Decadal Survey to optimize its network of missions to address system science. The potential for an HSO from the proposed THEMIS orbit adjustments and the concurrent availability of ARTEMIS lies beyond simple alignments and datasets. It is a comprehensive solution of data integration based on the grass-roots and mature SPEDAS software. The software plug-ins already developed for many datasets beyond THEMIS serve as a model for upcoming missions and have already been underwritten by the MMS and Van Allen Probe PI teams. Beyond data plotting and analysis, these tools integrate the community itself. By enabling efficient data tool (in addition to data or plot) exchanges, they also enable high-level, efficient science interactions.

The top level scientific rationale for executing this plan is the realization that kinetic processes in all regions affect fundamental energy exchange on global scales. Aside from local studies drawing inferences regarding global behavior, we presently do not know in detail how global forcing drives local processes. For example global flux transport in the Earth's lobes over 10s of R_E in the mid-tail is related to electron-scale conversion at reconnection fronts over 10s of km in the near-Earth region, yet only now can we begin to piece together this relationship from simultaneous measurements at disparate locations. Similarly, seemingly uninteresting intervals of pristine solar wind can drive dramatic variations in the pressure applied to the magnetosphere and recurrent large amplitude ULF waves at geosynchronous altitude. Finally, in the inner magnetosphere, hiss waves directly powered by chorus leakage into the plasmasphere work against chorus and nightside localized injections to establish the geoeffectiveness of a given global solar wind input. Key to the generation of these waves is the rate and intensity of localized injections from the nightside. These represent the only means by which enhanced tail fluxes can break through the open drift shells and replenish radiation belt and magnetospheric fluxes at sufficiently large energy such that wave-acceleration can lead to relativistic particles there. The availability of ARTEMIS as a high-fidelity, pristine lobe flux monitor (total magnetic energy available) and solar wind monitor (the pristine "driver") presents a critical asset for the space physics discipline, beyond ARTEMIS's in situ contribution to kinetic studies of reconnection fronts, upstream particles and plasmoids.

The considerations above suggest that only a coordinated observational strategy bringing together multipoint missions with a well-choreographed mission strategy can bear high-quality results and take full advantage of the developing Heliophysics System Observatory. THEMIS's approach is to help the discipline do just that and is explained below.

3.1 PSG#1: An Optimal HSO

In FY14 THEMIS plans to continue according to the plan stated at SR10, namely to separate P3-P5 by 8-8-8 hrs along-track to provide optimal, rapid coverage of radiation belt PSD with time (Fig 3A). THEMIS will simultaneously prepare to place its spacecraft in alignment with the proposed line of apsides of MMS at launch. This occurs by imparting significantly reduced perigees and apogees to P3-P5 such that their lines of apsides drift fast enough to match those of MMS during the early part of the mission. For a wide range of MMS launch dates the THEMIS mission design analysis shows that THEMIS will be able to match MMS's line of apsides during the first MMS tail season from around December 2015 to January 2016, depending on MMS launch date. After that time THEMIS will "lock" its line of apsides and periods in phase with those of MMS. At that point THEMIS will also adjust its orbits to become a large scale (ion inertial scale to MHD scale) tetrahedron with MMS at one of its vertices. While THEMIS will be performing its own unique science on reconnection fronts, energy transport and dissipation, it will also provide the contextual measurements within which MMS will be performing small-scale (electron inertial scale to ion inertial scale) reconnection observations. From that vantage point and during FY16-17, THEMIS will conduct nightside and dayside observations for a year (Fig. 3B). During this period ARTEMIS will provide important coordinated measurements in the tail and at the dayside.

When MMS raises its orbit to 23R_E, THEMIS will also raise its apogees, to create resonant orbits with MMS. THEMIS P3 has sufficient fuel to raise its orbit even beyond 23R_E, so such a configuration is not a resource problem. However, the scientifically optimal configuration to understand energy flow through the magnetosphere and link MMS's reconnection observations to their effects in the inner magnetosphere as measured by the Van Allen Probes is to place THEMIS in relatively large separations over 1-2 R_E range radially and azimuthally as shown in Fig. 3C. From that vantage point THEMIS can tell which reconnection pulses are geoeffective and which aren't, as

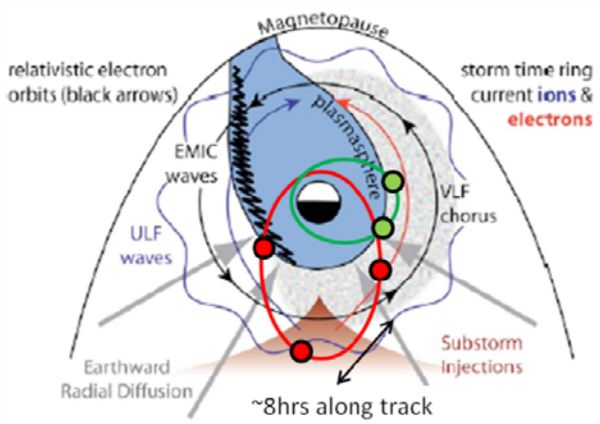


Figure 3A: PSG#1 configuration for FY14. THEMIS (red orbit will be studying large scale cause and effect relationships of sources and sinks in phase space density within the magnetosphere (in conjunction with ARTEMIS observations of the solar wind and tail reconnection drivers), and will optimize its observation strategy for full coordination with the Van Allen Probes, it will also be changing its orbits to impart a significant line of apsides drift to match those of MMS during the early period of MMS's mission. Additional data brought to bear in this period with THEMIS's SPEDAS common analysis system are ground based arrays and GOES particles and fields.

well as measure the energy conversion occurring during the shrinkage of the recently reconnected flux tubes. ARTEMIS, at the same time, will be able to measure (in addition to the total energy release in the tail) the effects of reconnection at the distant tail and the energy conversion exiting the magnetosphere from the tail. This orbital configuration will last for two years, i.e., FY17 and FY18 (as THEMIS's prime mission configuration of tail alignments did). These two years will provide our field with data to be analyzed for decades to come.

En route to its rendezvous with MMS in 2015, THEMIS will use a string-of-pearls approach to obtain conjunctions with MMS during its first dayside season and during part of the first tail season (depending on launch date). This configuration is ideal for conjunctions when the lines of apsides still differ by 25° or more (Fig 3D). This configuration was also used previously by the THEMIS coast-phase in 2007 and resulted in very significant science yield in its own right (many of those results have been summarized in two special AGU publications, in GRL in JGR, in 2009). With MMS's positioning in the context of THEMIS's coast phase configuration, MMS stands to

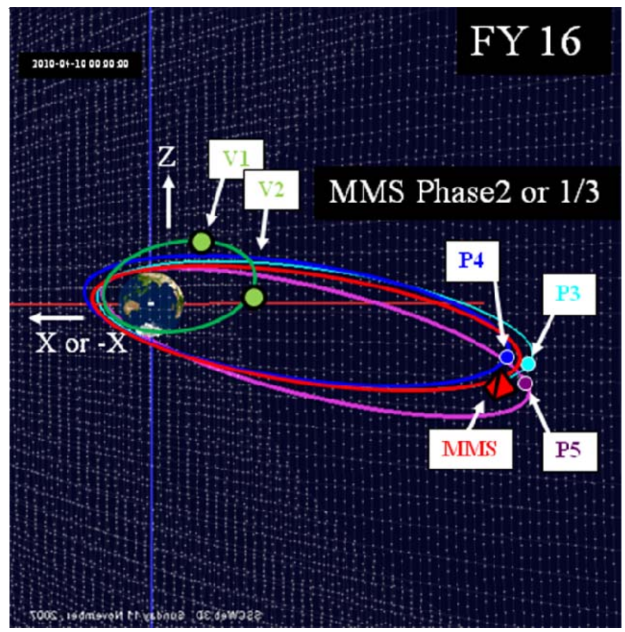


Figure 3B: PSG#1 configuration for FY16. THEMIS P3-P5 will be at the three vertices of a large-scale tetrahedron while MMS will be at the fourth vertex. ARTEMIS will provide solar wind and global flux content measurements, while conducting its own fundamental science discoveries. Coordination with Van Allen Probes teams and increased data volumes (near continuous) in Fast Survey on THEMIS will continue in order to optimize an HSO strategy for NASA's Heliophysics Division.

benefit significantly from the resultant contextual THEMIS observations, even without an optimal large-scale tetrahedron surrounding it.

3.1.1 At the nightside. From these vantage points, THEMIS and ARTEMIS, will be able to uniquely address the science of energy conversion in the 12-16 R_E regions in the magnetotail as will be described in PSG#2, which is a subset of PSG#1. However in FY15 and FY16, using the unparalleled opportunity of measurements from MMS within its ion-scale separations and volume, THEMIS will be able to reconstruct the flow of electromagnetic energy into particle kinetic, thermal energy, Poynting flux and waves. Moreover, as MMS observes the off-diagonal terms in the electron pressure gradients, which result in irreversible energy conversion within reconnection fronts, THEMIS will be able to observe the field-aligned wave Poynting flux emanating from this kinetic process enroute to the auroral ionosphere. Such correlative measurements will be far more powerful than the sum of separate measurements from the individual missions. And in conjunction with the Van Allen Probes, THEMIS will be able to address how much of (and in what way) the original tail lobe magnetic energy affects inner magnetosphere particle acceleration and transport.

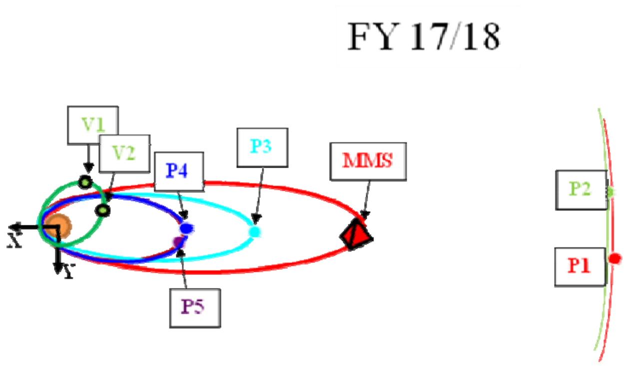


Figure 3C: PSG#1 tail configuration for FY17/18. THEMIS P3-P5 will be at resonant orbits such that during every MMS orbit at least one THEMIS probe is lined up with it along the Sun-Earth line, and periodically (once per 2 MMS orbits) all THEMIS "low" probes will line up with MMS. ARTEMIS will be conducting tail measurements as well, once per lunar month. Note that the same configuration applies on the dayside. This unprecedented strategic use of HPS assets cannot materialize ever again with satellites providing such high quality measurements. Even if constellations happen in the next two decades, their measurement cadence, fields instrument sensitivity and particle geometric factors will likely never be as high as those of MMS, THEMIS/ARTEMIS or the Van Allen Probes.

During FY17/18, THEMIS "low" and ARTEMIS will directly address questions related to global energy conversion from kinetic processes at and beyond $14R_E$, the spatial gradients of plasma pressure, and field aligned current generation from vorticity as the dipolarization region expands tailward. These goals are the same as in PSG#2. But in addition to that, the presence of MMS between THEMIS "low" and ARTEMIS, and the high volume of science data yield enabling routine correlations with the Van Allen probes, will result in transformational changes to our understanding of large scale coupling. This is because while THEMIS "low" and ARTEMIS will be studying the effects of reconnection, MMS will be studying its drivers in situ. Correlations from a global vantage point are critical for progress. For example, the inability of the flux tubes to convect inward of THEMIS due to increased entropy may quench the reconnection rate of the reconnection observed at MMS. On the other hand tailward progression of the dipolarization past THEMIS, MMS and ARTEMIS may initiate a new reconnection site between THEMIS and MMS such that the remaining stored magnetic flux (monitored by ARTEMIS) will be expelled from the system. Such key questions could never be posed without the simultaneous availability of all HSO assets.

3.1.2 At the dayside. Similar to the nightside, THEMIS "low" together with ARTEMIS will be addressing how kinetic processes partake in global forcing and energy transportation. The spacecraft alone and with fortuitous conjunctions with other NASA assets will be studying the under-explored region of $12\text{-}16R_E$, where ion foreshock phenomena, and the flow shear affect energy input by magnetopause pressure pulses or reconnection. These are objectives of the PSG#2 as well. But beyond these, the availability of MMS in FY15/16 within the THEMIS broad, ion-to-MHD scale string of pearls or tetrahedral formation results in an unparalleled opportunity to study dayside reconnection drivers with exquisite detail on both ion and electron scales simultaneously. The availability of ARTEMIS providing high-fidelity pristine solar wind information, and Van Allen Probe data providing information on the effects of dayside processes creates a system observatory of unparalleled power. For example, while THEMIS will be testing the Swisdak et al., [2010] theory with its three spacecraft measuring inflow and outflow conditions simultaneously, MMS will be making detailed measurements at the reconnection site to determine if the asymmetric nature of reconnection and the effects of electron pressure gradients are indeed the ones responsible for the success of this kinetic description. At the same time, in the inner magnetosphere, the Van Allen Probes will measure the effects of reconnection and pressure or foreshock wave related boundary variations on ULF wave generation and related acceleration of energetic particles in the aftermath of CIRs that will abound during the upcoming peak and declining phase of the solar cycle.

In FY17/18, going beyond the PSG#2 objectives, THEMIS's will make observations of the ion foreshock and magnetopause reconnection under flow shear in conjunction with simultaneous MMS observations of these phenomena at larger distances. According to Turner et al. [2013] and Hartinger et al. [2013], foreshock bubbles are not only ubiquitous but also the most dynamic variations under even steady solar wind velocity and dynamic pressure. These extend far upstream, grow and pick up energy as they approach the shock. The combination of ARTEMIS, MMS and THEMIS "low" lined up along the Sun-Earth line provide a unique opportunity to study particle acceleration as well as spatial evolution of such kinetic phenomena, with applications to fundamental processes across all Heliophysics systems. In particular here at Earth these affect ULF wave growth and subsequent relativistic flux increases, but also such pressure variations in the aftermath of CIRs drive dayside chorus waves that may also play a role in electron energization [Li et al., 2012]. Particle Fermi acceleration within such foreshock bubbles may be the origin of galactic cosmic rays at stellar shocks as well as interplanetary shocks. Such phenomena can be studied upstream of Earth's magnetosphere thanks to MMS's high time resolution measurements in conjunction with ARTEMIS and THEMIS "low". These particles may also contribute to local upstream pressure variations, as well as increased fluxes in the 10s of keV range (Fig. 2H) that, in the presence of southward interplanetary field, may seed production of relativistic particles inside the magnetosphere. The Van Allen Probe measurements will then be used to assess how much of this radiation is "geoeffective" from the vantage point of the inner magnetosphere, and regardless, how these phenomena affect particle acceleration in that environment.

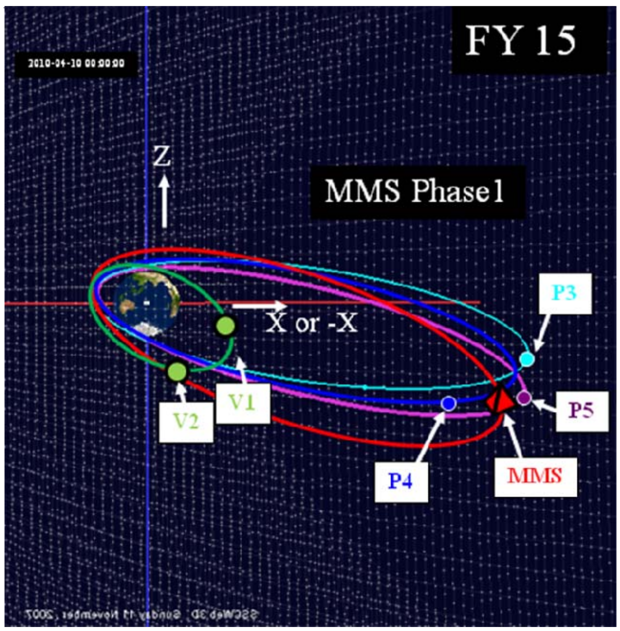


Figure 3D: PSG#1 "string of pearls" configuration for FY15. While MMS will be in its first dayside season, THEMIS P3-P5 will perform a strategy of bracketing the MMS near apogee traversing the location of MMS one after another, providing from inter-spacecraft separation of a few RE a repeated crossing of the MMS altitude and bracketing MMS near the magnetopause. This was a very successful strategy during the THEMIS coast-phase era. In the meantime, coordination with Van Allen Probes (shown as V1, V2 in green) is key to THEMIS's science objective to link local kinetic physics to global forcing and consequences.

3.1.2 In the inner magnetosphere. Going beyond the goals of PSG#2 to study correlations amongst its own P3-P5 spacecraft and fortuitous conjunctions with other assets, THEMIS proposes to be at the forefront of a concerted effort to optimally unite current and upcoming platforms into a common data analysis environment with unprecedented capability. By doubling its highest quality data recovery THEMIS will ensure optimal data return (>20hrs per day of Fast Survey on P3-P5) such that only rarely, if ever, would the analysis of interesting events be hampered by low cadence. THEMIS promises to study drivers of chorus, EMIC waves, hiss and ULF waves that affect radiation belt and ring current growth from its unique vantage point the nightside and dayside. On average in the planned MMS conjunction scenario THEMIS P3-P5 will still provide at least one full radial PSD cut of equatorial fluxes each 8 hours (and in the early years more rapidly than that). The availability of Van Allen Probe data and the PSG#1 mode of THEMIS science operations enables correlations of the highest caliber between the two missions, as well as with MMS. For example as THEMIS observes the generation, properties and propagation of chorus waves and injections outside of $7R_E$, Van Allen Probes are able to then use this information to determine if hiss or EMIC waves can be explained as result of that input. Thus the THEMIS team can determine the effects of external drivers on the inner magnetosphere, while the Van Allen Probes team can determine the importance of various drivers for local growth.

During FY17/18, correlations with MMS at distances intermediate between THEMIS "low" and ARTEMIS will provide a comprehensive understanding of drivers from larger distances both on the dayside and the nightside.

As discussed in section 2.3, it is the community's latest understanding that a combined "system" approach towards studying the inner magnetosphere source and loss processes is essential, and key to this understanding is a high degree of correlative measurements from high L-shells [Turner et al., T2013]. And as Gabrielse et al., point out, transient electric field pulses toward the inner magnetosphere from the nightside have the potential to explain not only wave generation and subsequent particle acceleration, but also the seeding of the initial inner magnetospheric flux with 10s of keV "pre-accelerated" electrons that can then be further enhanced to relativistic energies. THEMIS "low" and ARTEMIS hope to be at the center of NASA's systematic attempt to take advantage of the line-up or assets and enable system-wide studies of inner magnetospheric processes.

3.2 PSG#2: The "baseline" approach.

Should HQ does not approve the optimal utilization of THEMIS's available fuel and capabilities for system-wide science, THEMIS plans its "baseline" approach. This approach assumes that the guide will be restored (as anticipated) to its value prior to the clerical error due to the shifting of resources across fiscal year boundaries, and in accordance to the planned and negotiated contract. In that case THEMIS plans to optimize its 12hr Fast Survey (FS) collection strategy between its own assets, and explore the generation, evolution, global drivers and consequences of kinetic processes at the nightside and dayside, by expanding its observation area outward from 12RE to 16RE to explore with multi-point observations the previously this important, under-explored region of the equatorial magnetosphere. THEMIS will be at the nightside in Fall and winter in the upcoming few years, which brings into play its powerful ground based array of auroral optical imagers in addition to a growing list of ground magnetometer networks from across the world under one analysis system. THEMIS will also use fortuitous conjunctions with Van Allen Probes and GOES but does not rely on those to complete its goals.

3.2.2 On the nightside. From the vantage points of XY and YZ separations over 1-2R_E and from radial distances beyond 12R_E, THEMIS and ARTEMIS will be able to uniquely address the science of magnetotail energy conversion in the 12-16 R_E region during the collapse of incoming flux bundles within reconnection fronts. These fronts begin at substorm onset (and they are important in that regard) but they are even more important energetically in late substorm expansion phase and recovery phase, during which most of the lobe energy is tapped and released into the aurora. After all, it is in recovery phase when most ionospheric outflows, and the most intense ionospheric currents are observed. During the inward motion of reconnection fronts at onset the important question is the interaction and propagation of the front un-abated by the push-back from the inner magnetosphere. Why does that happen at a relatively steady speed, and what dictates the energy conversion under such conditions? During the tailward expansion of the dipolarization (at late substorm expansion, or recovery) the questions are different: How does the ionospheric current get generated and how does the dominant energy of the magnetic field get partitioned through the incoming reconnection front into the various forms of particle energy and/or waves? These questions can only be answered by spacecraft distributed on the proposed scales. The region from 12-16R_E is where the dipole transitions to a tail-like configuration when dipolarization expands tailward in the course of substorm expansion/recovery; it is the region of the most intense cross-tail current during the phase of most intense energy release in the course of a substorm.

ARTEMIS has a unique and important role to play in this strategy. Recent results demonstrate that the total energy content of the tail can be well monitored from the lunar distance, and when compared against the energy (lobe flux) input thanks to the solar wind electric field, the difference results in an accurate determination of the instantaneous energy release (and flux transport) in the tail. These observations of global flux transport and energy conversion rate, when compared to local plasma sheet measurements at the inner magnetosphere, promise to reveal an accurate picture of how kinetic processes at the inner magnetosphere are affected by and partake in global flux and energy transport.

The THEMIS P3-P5 radial distance will increase progressively and will be adjusted in accordance with scientific lessons learned from the early parts of this observing strategy. Representative orbits in YZ-plane alignments are shown in Fig. 3E. Orbits in XY-plane formation are not shown here but are easy to visualize. A similar strategy was employed in 2008 and 2009, to explore pressure gradients and flow shears inside of 12R_E (the region of interaction between fast flows and the dipole in the early stages of substorm expansion phase onset) resulting in discoveries that have reshaped the field. New discoveries pertaining to energy conversion at substorm recovery (the most energetic portion of a substorm) await the mission in this exciting period ahead.

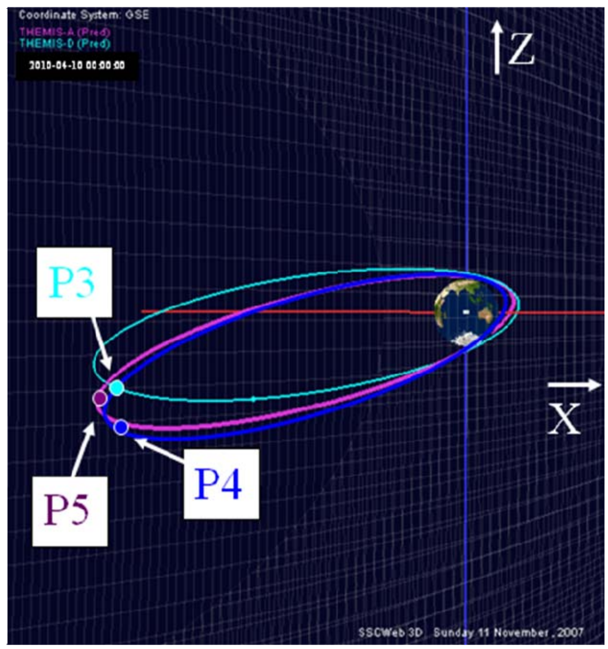


Figure 3E: PSG#2 configuration for FY16. In this period THEMIS P3-P5 will study the YZ variation of energy conversion regions within reconnection fronts, the location of the most significant conversion of lobe magnetic energy into particle kinetic and thermal energy as well as waves. It will do so progressively beyond 12R_E (e.g., at 14R_E apogee in FY15) in order to be less affected by the significant interaction of these fronts with the dipolar region. XY separations over 1-2R_E distance will be taken up in FY15, and FY18 out to ~16R_E. In FY17 YZ separations will be explored again at ~15R_E. A similar strategy at the dayside ensures the different altitudes do not affect adversely differential precession.

3.2.2 At the dayside. Transient phenomena at the dayside can be studied in the formations suggested in Fig. 3E out to 16R_E extremely well with THEMIS. The objective of this strategy at the dayside is first to enable correlative multipoint in-situ observations of such kinetic foreshock phenomena on MHD scales (1-2 R_E) comparable to the scale size of these structures in the equatorial magnetosphere. This will take place with XY and YZ separated probes in the manner indicated in Fig. 3E. Second, to enable an accurate understanding of the role of these kinetic phenomena for inner magnetospheric energy coupling. This will take place with XY separated probes 3 orbits every 4 (or 7 orbits out of 8, depending on apogee separation) basically relying on two THEMIS "low" spacecraft to study the foreshock and one probe interior to the magnetosphere. Third, to enable extension of studies of the dayside equatorial magnetopause reconnection over ion-to-MHD scales from the subsolar magnetopause (during the THEMIS prime mission years) now to the flanks of the magnetopause, where flow shear affects the reconnection rate in ways that are not presently understood. This regime will not be studied by MMS because MMS will only traverse the dawn flank enroute to the mid-tail region, and will provide rapid crossings of it at very small azimuthal separations. THEMIS on the other hand can provide a very comprehensive dataset of separations appropriate for the KH and boundary layer wavelenths and flow shear scale sizes that affect reconnection there.

Again, ARTEMIS has a unique role to play at the dayside, in that it can provide the pristine, high-fidelity solar wind measurements that cannot be obtained by spacecraft at the L1 point because those are too far compared to scale sizes of structures in the solar wind. Moreover, ARTEMIS can study the effects of ion foreshock phenomena (upstream accelerated particles) that are evident at that distance routinely, and correlate those with observations of energy gain at the foreshock phenomena measured by THEMIS "low".

3.2.3 In the inner magnetosphere. THEMIS benefits from a very well characterized instrument suite which, although it does not extend far into the relativistic particle regime, can fully measure at larger L-shells the PSD of particles that become relativistic if they conserve their 1st invariant by the time they diffuse into the inner magnetosphere. Recent calibrations enable very accurate matching between low and high-energy spectra in individual look directions and as function of pitch angle. Wave instruments can fully capture the sub-16kHz, highest energy density waves responsible for most wave particle interactions. THEMIS "low" plans to use its orbital strategy to study from multiple vantage points, i.e., at high and low L shells simultaneously, the effect of transient energy releases at the dayside and nightside on driving inner magnetospheric waves and injections, and to study the effects of those waves and injections on inner magnetospheric particle energization. Specifically, THEMIS will use the rapid (once per 8hrs) radial PSD excursions on all probes for context, and place simultaneous observations of PSD sources and other drivers at apogee and of waves and other inner magnetospheric phenomena at the inner magnetosphere to understand how energy from transient phenomena couples into the inner magnetosphere at times of storms. This information will be combined with GOES, Van Allen Probes, THEMIS imagers/magnetometers and other allied ground based observatories to synthesize as complete a picture as possible from fortuitous conjunctions across these platforms.

3.3 If the guide remains

As explained earlier, the resultant toll from performing such a drastic (and we believe inadvertent) cut to the mission will be a dramatic decrease in science funding, albeit THEMIS orbits, mission and science operations will remain intact. The toll on science, however, mostly due to lack of active THEMIS scientists that would interact with other community members, would be a >45% loss on community wide productivity on THEMIS data, and >66% loss of science led by THEMIS personnel alone. Details on this are available in the technical and budget section.

4. Technical/Budget

4.1 Technical

4.1.1 Observatory and instrument status overview As of this writing, the entire THEMIS constellation is in outstanding health and performing nominally. Specifically all subsystems are as good as new. The added knowledge that the operation teams and scientists have of their specific characteristics makes data use much more powerful than that for a newly launched mission. The minor technical issues (see below) that have appeared since the last senior review have all been resolved with workarounds and without degradation in science.

THEMIS "low" probes P3-P5 are currently in orbits with 23hr periods with inter-spacecraft separations increasing from 2 and 4 hrs to 8 and 8 hrs between probe pairs – the latter will occur by early 2014 to enable planned science and optimal configuration for conjunctions with the Van Allen Probes. ARTEMIS probes P1, P2 are in nominal ~18hr period equatorial, stable lunar orbits (retro- and pro-grade respectively), performing nominal operations for planned alignments and joint studies with LADEE in 2014, and conducting optimal Heliophysics research as per plan. Ground-based optical and magnetometer operations continue nominally, but will become increasingly important during the northern winters of 2015-2018 when they will provide global context for both the THEMIS and MMS missions, whose apogees will lie in the magnetotail.

After more than 500 individual thrust operations, ~1000 shadow cycles, and approximately 6 years in orbit traversing the radiation belts there are no signs of any measureable degradation in the performance of any spacecraft or instrument subsystem, including the 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.

During the last 3 years there have been only two new hardware issues. Both have been resolved satisfactorily without any science degradation: 1) A micrometeroid severed one of P1's EFI wire boom spheres on October 14, 2010. The lost science can be recovered at low (spin-average) resolution by using the other (unaffected) boom pair. High-time resolution EFI measurements can still be obtained from potential differences between the remaining 3 spin plane probes; and 2) a Helium bubble developed inside one of the tanks on P4 (THEMIS-E) that can be controlled by a few back-and-forth actuations of the latch valves (over the remaining fuel lifetime) when fuel in the two tanks isotropises again. This operation may need to happen once or twice over the next 5 years of THEMIS operations.

Instruments nominally 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 35000 passes have been completed to date in lights-out mode. Average downlink performance presently exceeds requirements by 50%, thanks to the ground system performance. As of the fall of 2012 the operations team has been acquiring some additional FS data beyond the nominal 12hrs/orbit to accommodate science needs for Van Allen Probe conjunctions and practice for optimal operations if so requested. This is to gain experience with the WS1 antenna if THEMIS receives approval to implement additional coverage for optimal use of Heliophysics System Observatory assets as called for by PSG#1. Scheduling has proven quite time consuming and operations have been curtailed to a best-effort basis beyond the 12hrs required from the beginning of 2013. Staffing increases and science optimization (closely coordinated with the science team) can still enable nearly full coverage in FS mode if THEMIS receives approval to proceed. Without approval, we will return to nominal 12hr FS coverage.

ARTEMIS operations continue with DSN support at a rate of one 3.5hr contact per day. Nominally, they collect one time-based periapsis burst and one onboard trigger-based apoapsis burst per FS interval. Optimizing triggers for the new science goals will not incur any additional cost.

4.1.2 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 occur months in advance for nominal planned maneuvers with a quick turnaround reaffirming conjunctions, shadows, and fuel budget. Product generation based on updated ephemeredes 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, certified USN and HBK stations support THEMIS when needed to fill gaps, and NASA WS-1 has been certified and supports THEMIS contacts when high altitude contacts are needed to obtain FS data beyond 12hrs for additional Van Allen Probe conjunctions coverage. Additionally, DSN has been supporting ARTEMIS with its 34m antennas as mentioned earlier, and scheduling and tracking is proceeding nominally. The NTR T-1 line from GSFC to the MOC over the Open IONet and 3 voice loops continue to function nominally.

4.1.3 Mission operations. Thanks to the increased familiarity of the operations team with the propulsion and thermal systems of the probes in both Earth and lunar orbits 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 FY14/16 in conjunction with MMS. Similar very fine maneuvers have already been performed in FY11/12 for a few 100km separations on a best effort basis. Based on that experience, the experience from navigation and mission planning from ARTEMIS and the relatively large separation requirements (1000km or more) of the THEMIS tetrahedron for MMS conjunctions, the team expects no problems meeting the science needs to place the THEMIS spacecraft in a large scale tetrahedral formation around the MMS position near apogee, assuming good coordination with the MMS design team.

If PSG#1 is approved, THEMIS will execute an observation strategy and ascend profile similar to that for the prime THEMIS mission in FY17/18, except that orbit periods will match those of MMS rather than be sidereal. If PSG#2 is executed throughout FY15-18, the planned resonant orbits of satellite pair P4 and P5 (with similar periods) with satellite P3 (with a period resonant to those of P4, P5) will occur at progressively larger apogees from the current $11R_E$ out to $16R_E$. These orbits will be far easier to achieve than those for PSG#1 due to the greater (20%) tolerance in the separations and the larger ($1\text{-}2R_E$) interspacecraft separations desired. All probes will retain healthy fuel reserves after accounting for de-orbit, thereby permitting exciting possibilities for joint work with MMS beyond FY14.

Instrument operations. Under the PSG#1 plan, FS intervals for P3, 4 and P5 will be commanded at 20hrs/day (leaving 4hrs of SS operations near perigee). ARTEMIS P1 and P2 operations will be coordinated with MMS apogees when in the magnetotail or on the dayside to enhance the return under a system observatory approach. In that plan the FS intervals will be centered on times of optimal joint HSO science, even though FS durations will remain the same. Under the PSG#2 plan, THEMIS operations requirements will continue as they are today, i.e., 12hrs/orbit of FS with 1.2hrs/orbit of PB collection. Under the same plan, ARTEMIS P1 and P2 operations will remain nominal, i.e., 8hrs of FS out of which 1hr brackets periselene; and simultaneous FS intervals on both ARTEMIS spacecraft. Often more than the minimum requirement is downlinked thanks to the use of high-performance DSN antennas with higher link margin than those assumed in the planning. When in the magnetotail, FS time assignments nominally prioritize the pre-midnight sector to capture plasmoids and tailward/Earthward fast flows; those result in tens of hours of continuous coverage, in exchange for lower coverage near the flanks and in the magnetosheath. These are coordinated by a scientist interested in the tail science and with appropriate expertise.

Instrument operation staffing levels are assumed as required to execute the PSG#2 baseline plan in FY13/14. Significant savings from operational simplicity, automation and familiarity of the team with instrument operations have already significantly reduced the mission and science operations personnel in FY14/15 (relative to that in FY11/12) and no further reductions are possible.

4.1.4 Science operations and community support. Thanks to continuous data analysis, calibrations of the instruments have evolved and L2 data have been re-generated a few times and have been updated at SPDF. The primary updates are noted here, in order of importance:

1. FGM magnetometer observations are now routinely despun during shadows (despite the lack of a sun-pulse the moments of inertia of all spacecraft have been modeled and a spin-phase good to ~1° has been released with the nominal despinning software). This is very important near the lunar wake and pre-midnight when shadows would otherwise prevent analysis in the midnight sector where substorms often occur. This was never a mission requirement but nonetheless has been solved. The modeled phase is then used to despin particle and EFI data (including the velocity and pressure tensor). Available since 2012.
2. EFI electric field observations have seen phase corrections of the 16kS/s data. Its data now match the phases expected for chorus waves, allowing Li et al. (2013) to calculate Poynting fluxes at the highest possible resolution. This has been available routinely for the last 2 years.
3. SST energetic particle fluxes have now been fully calibrated by modeling: i) the energies using GEANT4 simulations, ii) the dead layer evolution with time by comparison with ESA spectra, and iii) the response as a function of detector for isotropic flux conditions to determine relative anode efficiencies. Software enables recomputation of the flux at pre-set energies for partial moment generation and for spectral plots. Clean fluxes from the anti-coincidence channels are now available routinely. All the above changes are implemented with a single keyword, on the fly, by publicly available software since December 2012. After 2013, the L2 data will be created for distribution through SPDF.

Additional instrument calibrations are recorded online at the THEMIS web site (themis.ssl.berkeley.edu) under: "software→enhancements" or directly at: http://themis.ssl.berkeley.edu/themisftp/SCI/Soft/Progress/.

In addition, software plug-ins have been developed for multiple ancillary data and are discussed further in the MAP. Here we only mention that ground magnetometer networks from Alaska, Canada, Greenland, Scandinavia, Iceland, Russia and the North-South American chain McMac have been incorporated (http://themis.igpp.ucla.edu/instrument_gmags.shtml), and additionally GOES and SuperDARN load and analysis routines have also been implemented. Instrument and software training sessions for the community and routine community support on instrument specifics and software for calibration and analysis are implemented through a "Help Request" line on the THEMIS Web page (under software → Themis Science Support Team). The THEMIS MAP provides more discussion along these lines.

5. 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. Five press releases or press conferences around the EGU 2010, the ARTEMIS lunar insertion in 2011, publications in Science by Nishimura et al., 2010; and in Nature Physics by Turner at all et al., 2012 and others resulted in wide acceptance by the media and coverage by the press, including publications in National Geographic, NBC and dozens of other media organizations around the world (Fig 5A) reaching audiences of millions. We gave presentations at the Maryland Science Center, and on major Science Day events at UCLA/UCB multiple times where we have engaged audiences of thousands.

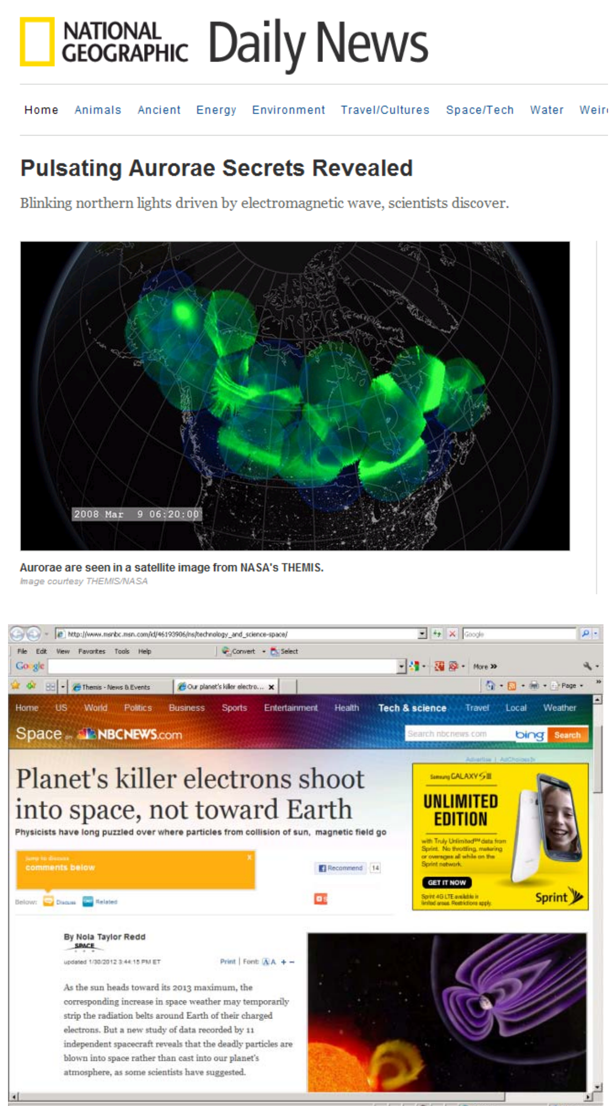


Figure 5A: THEMIS and ARTEMIS discoveries reach audiences of millions each year through press releases organized by our public affairs office at NASA/GSFC surrounding science discoveries in high-impact publications.

6. References

References appearing as: "name, T20xx" are from THEMIS or ARTEMIS and can be found at:
http://themis.ssl.berkeley.edu/publications.shtml
Other references:
Angelopoulos et al., Electromagnetic energy conversion at reconnection fronts, Science, submitted, 2013.
Omidi, N., et al., JGR, A06204, 2010.
Petrinec S. and C. T. Russell, JGR, 137,1996.
Sergeev, V. A., et al., Direct evidence of a two-loop pattern of the substorm current wedge (SCW2L), JGR, submitted, 2013.
Swisdak, M., et al., ApJ, 710, 2010.