D. SCIENCE INVESTIGATION

THEMIS ["Time History of Events and their Macroscopic Interactions during Substorms"] will determine the onset of the macroscale substorm instability. The primary quest of THEMIS, "where and how are substorms triggered", has been identified by the National Research Council (NRC) as one of the main strategic questions in space physics[1]. Five identical microspacecraft (probes) with carefully designed orbits near the equatorial magnetotail provide prolonged tail-aligned, cross-tail and cross-sheet conjunctions. In each of those ideal conjunctions THEMIS has the opportunity to study 50-100 substorms. Comprehensive in-situ particles and fields measurements in space together with simultaneous, ground-based, global measurements of auroral onset will establish macroscale plasma interactions over scales ranging from 0.3 to 20 R_E. The primary focus of THEMIS is the region of 8-10R_E (where onset auroras likely map). Although THEMIS does not visit the tail reconnection region (which will be studied in situ by MMS) because it is not concerned with the reconnection process itself, it remotely senses reconnection onset to place substorm onset in the context of global circulation. Thus, in terms of the processes studied, the scale-size of those processes and the region visited THEMIS is complementary to MMS. UC Berkeley has managed two recent Explorer missions and has a 30 year long history of on-time, on-budget development and successful flight of instruments on SEC missions. THEMIS addresses unique science objectives and is a technological pathfinder to future NASA STP missions.

D1. SCIENTIFIC GOALS AND OBJECTIVES

a. Goals and objectives of investigation

A substorm is an avalanche of small-scale magnetotail energy surges[2] feeding from solar wind energy previously stored in the magnetotail lobes. During its course auroral arcs intensify, move poleward and break up in smaller formations[3]. A substorm has well demarcated global evolutionary phases corresponding to unique stages of an instability of the coupled solar wind-magnetospheric circulation of energy and magnetic flux. These unique stages are: energy storage (growth phase), explosive release (onset) and eventual ionospheric dissipation (late expansion and recovery phases). Thus a substorm represents a fundamental mode of global circulation of energy and magnetic flux transport throughout Geospace. This global, macroscopic instability is as central to space physics and space weather as the extratropical cyclone is to meteorology and weather. Despite the elemental nature of the substorm process lack of appropriate spacecraft conjunctions from previous missions resulted in a contentious set of theories for its description. At question is not simply which is the operant plasma micro-instability at onset. Rather, even the location, onset time, extent and motion of the magnetotail energization process leading to the macroscopic substorm phenomenon are still unknown[4].

	Science Objective	Science Goal
Primary	Onset and evolution of substorm instability	Time history of auroral breakup, current disruption, and lobe flux dissipation at the substorm meridian by timing: • Onset time of auroral breakup, current disruption and reconnection within <10s. • Ground onset location within 0.5° in longitude and in space within 1R_E.
		Macroscale interaction between current disruption and near-Earth reconnection.
		Coupling between the substorm current and the auroral ionosphere.
		Cross-scale energy coupling between the macroscale substorm instability and local processes at the current disruption site.
Secondary	At radiation belts: Production of storm-time MeV electrons	Source and acceleration mechanism of storm-time MeV electrons
Tertiary	At dayside:Control of solar wind-magnetosphere coupling by upstream processes	The nature, extent and cause of magnetopause transient events.

Table D-1. *THEMIS's goals and objectives*

Resolving the substorm problem requires accurate timing of three disparate but well defined processes: ground auroral onset, current disruption onset at 8-10R_E and reconnection onset at 20-30R_E. Since these processes expand rapidly with time, knowledge of the onset location is as important as timing. THEMIS is the first mission specifically designed to determine the onset and evolution of the substorm instability. Towards this primary objective, THEMIS utilizes conjunctions between 5 identical probes on multiple period, near-equatorial orbits. Three inner probes (~1day periods) monitor current disruption and two outer probes (~2day and ~4 day periods) monitor lobe flux dissipation. The conjunctions occur near-midnight (i.e., near the substorm meridian) when a dense network of ground observatories monitors ground onset. The objectives and goals are summarized in Table D-1. The primary mission requirements and mission capabilities are tabulated in Figure D-1/A_I, while THEMIS's orbits are depicted in Figure D-1/B.

b. Significance of science objectives.

Substorms are ubiquitous at all solar phases and appear within all types of magnetospheric responses to solar wind input: Embedded within large

This is foldout Figure D-1

storms they influence storm development[5] and geoeffectiveness[6]. They bound the beginning and end phases of magnetospheric convection bays[7]. They are closely related to pseudo-breakups[8]. Understanding the substorm process is a prerequisite to understanding the geo-magnetospheric response to all levels of solar wind energy throughput. However, the objective of deciphering the mechanism of the substorm instability transcends its geophysical interest. It relates intimately to broader scientific questions, because it addresses basic plasma physics processes, such as cross-scale coupling between MHD and kinetic plasma instabilities[9,10]. Beyond purely scientific applications are matters of more practical value to society, related to space weather processes (such as storms), which affect satellite communications and ground electrical distribution, and are inextricably linked to substorms[5,6]. In summary, *substorms represent a fundamental mode of global magnetospheric circulation, a macroscopic instability whose phenomenological and theoretical understanding is crucial for space science, basic plasma physics and space weather.*

c. THEMIS's alignment with NASA SEC goals.

The THEMIS science is directly aligned with the Space Science Enterprise Objective[11] to "understand our changing Sun and its effects throughout the Solar system" and Research Focus[12] to "understand the space environment of Earth". The primary and tertiary THEMIS objectives are aligned with Quests II of the NASA Sun-Earth Connections Theme: How does our planet respond to solar variations? THEMIS's secondary objective is important for Quest IV of NASA's SEC Theme: How does solar variability affect society? In particular THEMIS's primary objective to understand the fundamental mode of energy, mass and flux transport in Geospace is a basic SEC question identified in the SEC Roadmap[13]. THEMIS builds on a close relationship between US academia and US industry. It leverages significant foreign instrument and science contributions. These practices are in accordance with SEC strategic plans[14]. An open data policy and a $4M guest-investigator program maximize benefits from the US science community.

d. Substorm phenomenology.

d1. What is known about substorms.

The components of the substorm instability i.e., Auroral Breakup, Current Disruption and Reconnection, evolve on a meso-scale range but interact over macroscales. Previous missions and fortuitous spacecraft conjunctions have provided a wealth of information regarding these substorm components.

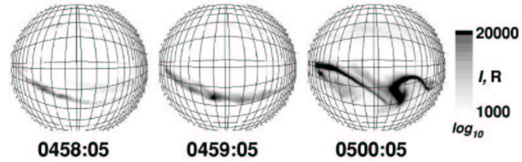

Figure D-2. *Substorm onset as seen from a ground all sky camera station[15]. Each line is 0.5 degrees in latitude (or 56km) and in longitude (or 31km).*

Auroral Breakup. High-sensitivity all sky imagers (ASIs) show that the pre-onset equatorward arcs undergo large-scale undulations with wavelengths of hundreds of kilometers (Figure D-2). This is ~6^o in longitude, which maps to a region of $\delta Y \sim 1R_E$ at the inner edge of the plasma sheet. Onset erupts in 10s at a folding of one such undulation.

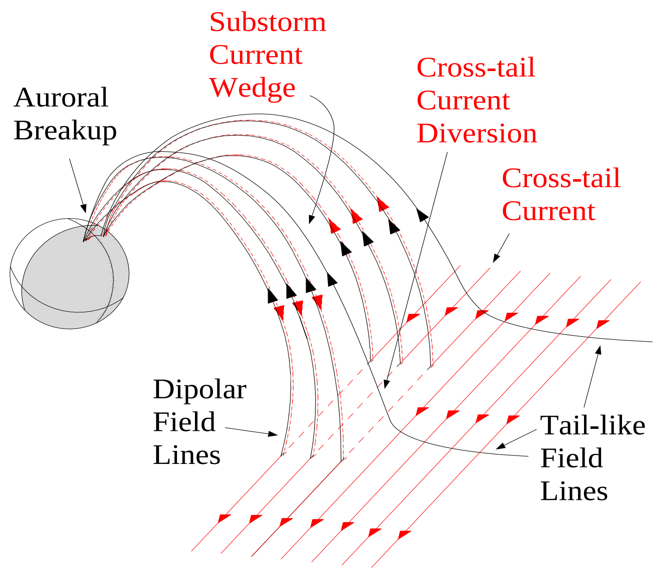

Figure D-3. *Development of the substorm current wedge through a reduction of the cross-tail current at 8-10R_E in the equatorial plasma sheet.*

Current Disruption (CD). An intense cross-tail current[16] (tens of nA/m^2), mainly supported by a duskward anisotropy in thermal ions (2-10keV), provides substantial free energy at growth phase at ~10R_E. At substorm onset the *current wedge* forms there (Figure D-3). This is an abrupt increase in the Z_{GSM} component of the magnetic field, accompanied by plasma heating. This morphological change of the field is consistent with a current-carrying particle distribution change[17]. It is modeled as a partial disruption of the cross-tail current and diversion *along* the field lines, *into* the auroral ionosphere[18,19] where it feeds into the breakup arc. It is often termed the current disruption (CD) process[20]. The hot, dipolar plasma originates in a small[21] equatorial area (~1R_E^2) and expands azimuthally[22] by ~10^o of magnetic local time (MLT) per min and radially[23,24] at ~200 km/s.

Reconnection (Rx). Further downtail, at ~25 R_E, there is evidence that *magnetic reconnection* takes place[25]. Fast, bursty, bulk ion flows presumably emanating from the reconnection site at Earthward speeds comparable to the Alfven velocity (1000 km/s), are also interpreted[26,27] as evidence of that process. Seen[28,29] as close to Earth as 10 R_E, such flows are often localized[30,31,32] (1-3 R_E) but are very efficient in energy and flux transport[33].

d2. The main question in substorm research.

Previous fortuitous spacecraft conjunctions have been unable to determine where and how the substorm instability starts because of their unoptimized vantage points. Presently all possible causal sequences involving auroral breakup, Rx onset, CD onset and external triggers are viable hypotheses[34]. In particular, CD and Rx might be causally linked, or proceed independent of each other. As an impartial and experienced researcher summarizes[35]: "*Observations are gradually leading to a coherent picture of the interrelations among these various onset phenomena, but their cause remains a controversial question. The abrupt nature of substorm onsets suggests a magnetospheric instability, but doubt remains as to its nature and place of origin. Measurements increasingly suggest the region of 7-10R_E near midnight as the likely point of origin*".

A number of substorm onset paradigms exist, but two of them can help epitomize the main ideas and reveal the primary observational requirements. These are the "*current disruption"* and the *"Near-Earth Neutral Line" (NENL)* paradigms.

Current Disruption paradigm. According to this paradigm an instability *local* to the current disruption region (8-10 R_E) is responsible for substorm onset[16]. The paradigm stems from two basic observations: First, the breakup arc maps near-Earth[36]. This has been reinforced by advanced mapping of auroral images from Viking[37], POLAR[38,39] and ground-based photometers[40,41]. Second, the cross-tail current density reaches tens of nA/m^2 and peaks near 8-10 R_E prior to substorm onset[42]. This happens explosively[43] suggesting that it is in *that* region that the free-energy source and trigger for the substorm auroral surges reside.

This paradigm suggests (Figure D-4) that Rx and fast Earthward flows are triggered by a CD-initiated fast mode rarefaction wave (V_x=-1600km/s) once it reaches ~25R_E. Flows cause neither the CD nor the auroral breakup itself. The relevant substorm component chronology appears in Table D-2.

Recent observational evidence in support of this paradigm comes from the observation that the particles energized first at the CCE spacecraft (located at 8-9 R_E) at onset are those with gyrocenters Earthward of CCE[20,45]. Finite gyroradius remote sensing applied on equatorial pitch angles produces the CD expansion's speed and direction ($\mathbf{V}_{xy}$). However, performing accurate CD onset timing requires knowledge of the CD expansion velocity at two probes which bracket the onset location. The probes should be at the neutral sheet (±2R_E) and near the CD location itself (±2R_E) so that the expansion speed will not vary significantly during its motion. Such timing has not been performed to date.

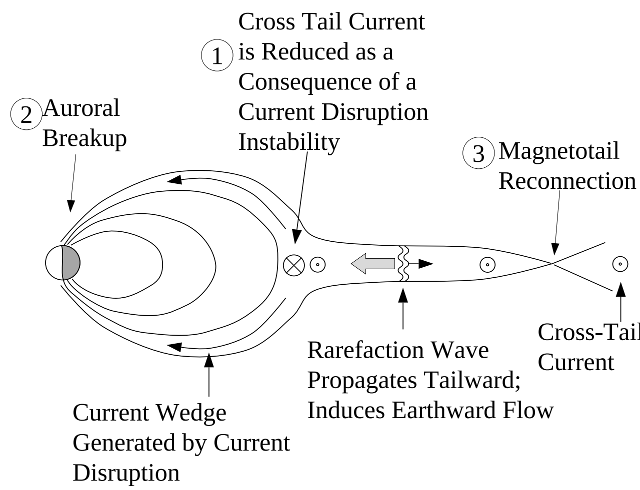

Figure D-4. *Time-history of events at the substorm meridian according to the Current Disruption model for substorms[44] (numbers indicate proposed chronological and causal sequence).*

Order	Time (s)	Event
1	t=0	Current Disruption
2	t=30	Auroral Breakup
3	t=60	Reconnection

Table D-2. *CD model event chronology.*

Near Earth Neutral Line paradigm. According to this paradigm[46,47], bursty flows generated by near-Earth reconnection[48] (~25 R_E) are responsible for substorm onset (Figure D-5). Observations pivotal for this model's development at the substorm meridian include fast tailward/Earthward flows [26,27] and plasmoid ejection[49,50] both timed to start within 1-2 minutes from ground onset.

This paradigm suggests that the flow kinetic energy is converted to particle thermal energy at the CD region. While heating generates a steep pressure gradient, the flow decelerates and deflects around Earth. The field aligned current created locally by these processes[52,53,54] leads to current disruption and auroral breakup. The recent observation that fast Earthward flows at 12-18R_E occur within 1min from substorm onset[31,51,55,56,57] has spurred renewed interest in field-aligned current generation in the NENL context. The NENL substorm component chronology is distinctly different from current disruption model's (Table D-3).

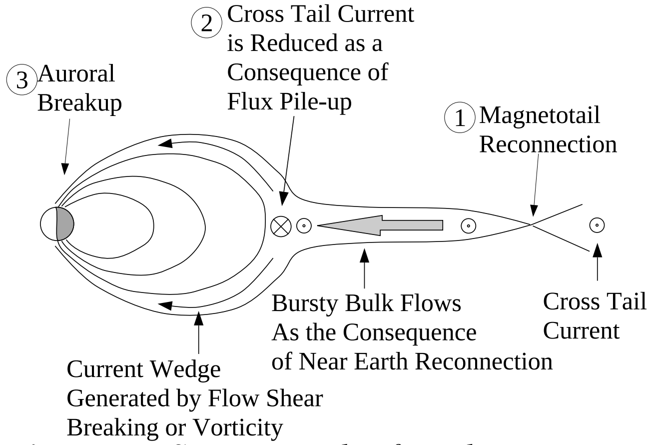

Figure D-5. *Same as D-4 but from the viewpoint of the NENL model for substorms[51]. Note the difference in the sequence of events.*

Order	Time (s)	Event
1	t=0	Reconnection
2	t=90	Current Disruption
3	t=120	Auroral Breakup

Table D-3. *NENL model event chronology.*

The NENL-predicted flow protrusion at 8-10R_E has never been reported at substorm onset, but has been seen during pseudobreakups, auroral streamer events[58,59] and at substorm recovery[60,61]. This has led to the suggestion[62] that pseudobreakup flows are CD onset triggers / substorm precursors. Alternatively: (i) The incoming flow may decelerate to compensate for the increasing magnetic field[63] or (ii) The flow may dissipate through field-aligned Poynting flux[64] along high latitude field lines[65,66]. The flow evolution and causal relationship (if any) to substorm onset is unclear, largely due to lack of tail-aligned spacecraft conjunctions.

Additionally, like for the case of CD onset detection, accurate Rx onset timing requires *two* probes at the plasma sheet, or its boundary, measuring velocity dispersed, field aligned, 30-300 keV particles. A strictly temporal interpretation of the dispersion provides L, the distance to the source[76,77]. A spatial interpretation[78,79] provides $L*V_E/V_B$. Here, V_E is the convection velocity along the flight path of the particles (inferred by the dawn-dusk electric field component or measured by the plasma detector). V_B is the Z_{GSM} component of the boundary velocity measured by finite gyroradius remote sensing on East-West particles fluxes. The latter is the more general interpretation (when $V_E = V_B$ we retrieve the temporal one), but can only be used if the Rx site is nearby (within ~5-10R_E), because the locally measured V_E/V_B is not necessarily constant along distant flight paths. Thus two probes at distances of 5-10R_E from each other should *bracket* the nominal Rx site. Oppositely-directed fluxes at the probes establish that the reconnection site is between them (nearby), justifying the assumption of a constant V_E/V_B. The two probes should observe the particles as the boundary expands over. Thus the two Rx monitors need not be at the neutral sheet but within δZ_{GSM}~5R_E of it. Plasma sheet Z-fluctuations affect little the timing capability because the active plasma sheet expansions are large relative to those fluctuations. Such accurate Rx timing has not been performed to date.

Other substorm models. Distinguishing between the CD and NENL models imposes similar observational requirements on timing and location as distinguishing between all substorm models. For example the Magnetosphere-Ionosphere (MI) coupling model[67] suggests that the substorm starts due to breaking of the Earthward flows at a rate >3mV/m/R_E, and the ensuing Alfven wave bouncing. Here the flows come first, as a result of mid-tail or distant tail processes and the remaining sequence of events is similar to the current disruption scenario. As in the current disruption model, Rx is not a necessary condition for onset triggering. But contrary to the current disruption model, the flows come first, as a result of mid-tail or distant tail processes.

Solar Wind triggering. Spontaneous[68] onsets and externally triggered[69,70] onsets (stimulated by sudden impulses, northward turnings or rotational discontinuities[71]) may exhibit different destabilization scenaria[72]. It is possible, e.g., that external triggers result in a NENL-like path to onset, whereas spontaneous onset substorms follow the CD paradigm prescription. It is thus important to classify substorms according to the external conditions in order to distinguish between different scenaria.

e. Mission requirements and mission design.

The science goals and objectives of Table D-1, and the previous discussion on substorm phenomenology lead to a set of mission requirements. These requirements are tabulated in Figure D-1/A_I.

For example, ground onset timing should be performed along the substorm onset meridian (δMLT~6^o which corresponds to 1R_E at the CD site) and must be better than the time scale of interaction of those processes (30s). Since CD onset is limited in δXY~1R_E^2 the CD monitors should be no more than δY~δX~±2R_E apart. Rx monitors should be around 20R_E and 30R_E, i.e., within ±5R_E of the nominal Rx site to ensure constancy of the measured V_E/V_B ratio. The neutral sheet location (maximum Z_{GSM} distance in winter solstice) determines the orbit inclination of both the CD and the Rx monitors. Diurnal fluctuations at 10R_E (δZ±2R_E) have little effect on the capability of the CD monitors to determine CD expansion speeds. Plasma sheet diurnal fluctuations at 20 and 30R_E (δZ±3R_E) are small compared to the ±5R_E tolerance. Additionally, the two inner probes in combination should permit cross-tail (δY~0.5-5R_E) or cross-sheet (δZ~1R_E) conjunctions (not necessarily simultaneously).

The objective to time auroral onset using <30s time resolution ASIs in the US/Canada fixes our probe apogees to US winter season, at central US midnight, i.e., ~6:30 UT (best performance of ASIs in winter). This in turn calls for orbit periods which are multiples of a day. Remote sensing requirements for both CD and Rx monitors are to measure near-equatorial fluxes. ACS control of 11.25^o is derived from the SST technical specifications. δB/B~10% requirements arise from the need to monitor the rarefaction wave (also the cross-tail current within δJ/J~10%, given a ΔB~B between probes at separation δZ~1R_E) In a minimum field of 10nT this renders the absolute stability requirement 1nT.

THEMIS should measure at least a few solar-wind triggered and a few spontaneous onset substorms (assumed equal chances to observe each). Thus at least 5 substorms should be observed in each probe conjunction configuration. Given a 3-6hr recurrence time for substorms[73], this necessitates 30hrs of useful data in each conjunction type.

THEMIS's orbit strategy accounts for >300 hrs of conjunctions in each conjunction type. We recognize that significant losses of useful events may occur due to plasma sheet fluctuations, lack of solar wind data, possible extreme event localization, and early evening/late morning substorms. Clear evidence that tail-aligned spacecraft equipped with THEMIS-like instrumentation can indeed monitor the progression of the incoming flows despite their δY~1-3R_E localization comes from fortuitous ISTP conjunctions during north-south arcs at late substorm recovery[58,59]. We anticipate that a number of events much larger than the required 5 will be available for study. Of those, a few high quality, clear and effective conjunctions will receive attention by a large number of people (like CDAW events).

The above strategy defines the mission design. Orbits are shown in Figure D-1/B_{II} and are tabulated in Figure D-1/B_{II}. Stability to J2 and lunar perturbations is established in Figure D-1/B_I. In particular THEMIS is immune to the differential precession of the line of apsides between the high and low altitude orbits, because it relies on mean anomaly phasing to obtain tail-alignments. Relative apsidal drifts of as much as 60 degrees can be balanced by mean-anomaly phasing.

THEMIS's orbits, instrumentation and time resolution are specifically geared towards resolving the present impasse on the onset and evolution of the substorm instability.

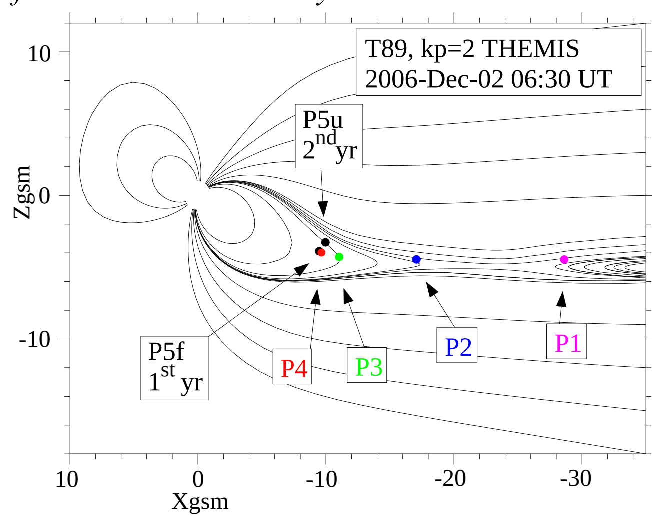

Figure D-6. *Meridional view of the THEMIS probe locations at midnight over North America. P5f, for fast gains 7minutes/day over P4, during year#1. P5u (up), is above P4 by 1R_E at apogee in year#2.*

f. Expected results

f1. Time history of events.

THEMIS probes will form more than 300hrs/yr (50-100 substorms[73]/yr) of tail-aligned conjunctions (all within δY=2R_E from P1) and will delineate the time history of events that compose the substorm process. In addition to WIND, ACE and SOHO, solar wind data from TRIANA and Solar Stereo will likely be available in THEMIS's time frame. With such data *THEMIS will account for the external conditions and distinguish between the different paths to substorm onset.*

CD onset determination. At speeds of 200km/s a current disruption onset $1R_E$ away expands over the THEMIS probes within 30s. THEMIS probes P4 & P3 (Figure D-6) will obtain timing information from the remote sensing (finite gyroradius) technique[20,45] applied to energetic ions. Boundary expansion speeds to within 10km/s and directions good to a fraction of the angular resolution of the ion detector[74,75] will be obtained. The onset time will be determined from the expansion velocities on the two nearby probes to a temporal resolution as good as the temporal resolution on the probes (3s). *THEMIS's temporal resolution provides current disruption onset timing to within 10s or better.*

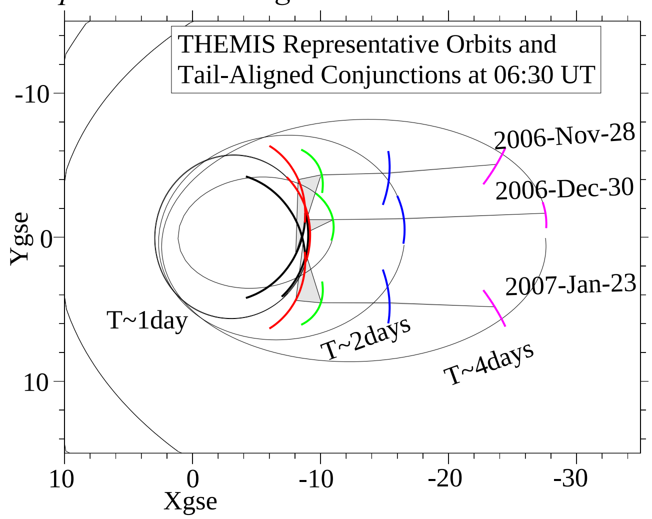

Figure D-7. *Equatorial view of THEMIS probe locations during tail-aligned conjunctions. Full orbits are shown only near winter solstice. Six-hour-long orbit segments centered at 6:30 UT are shown in color, approximately one month apart. Colors denote the different probes as in Figure D-6.*

Reconnection onset determination. THEMIS will time Rx onset by monitoring the arrival times of field aligned energetic particles from the reconnection site at its two outer probes (P2 & P1). Those are within $5R_E$ from the nominal site of reconnection ($25R_E$). Ancillary timing information will be obtained from the measured flow speed and other local observations[77,56] (electrons, waves, MHD pulse). *THEMIS's probe locations, temporal resolution (3s) and instrumentation will ensure reconnection onset timing to within 10s or better.*

Auroral breakup onset determination. Imagers or ground magnetometers can time onset far better than mid-latitude global Pi2 onsets[80,81]. THEMIS's dense network of white-light all sky imager and ground magnetometer stations in Alaska, Canada and the US at 1s resolution will ensure accurate determination of onset to within 0.5^o in magnetic local time (Figure D-8). Cloudy skies or moonlight can obscure, at times, part of those images. At those times, PiB (1-40s period, 3s nominal) pulsations[82], which are good substorm indicators[83,84], will determine onset time to within a few seconds. Substorm current wedge modelling from a dense North American network of auroral and mid-latitude magnetometer stations provides determination of the substorm meridian to within 5^o or better (still fulfilling the science goal of 6^o). Such modelling is routinely performed using data from the existing network of mid-latitude stations[85,86,87,88] and has been validated using global imaging[89]. In short *THEMIS's ground network of all sky imager and ground magnetometer stations has the density and time resolution to detect auroral breakup onset meridian and onset time nominally within $\delta MLT<0.5°$, $\delta t<10s$.*

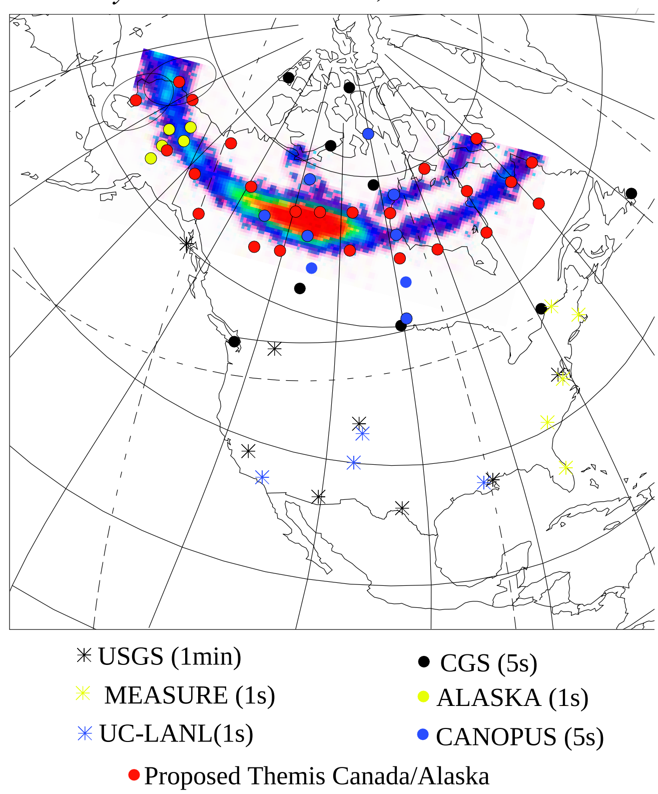

Figure D-8. *Locations of existing and proposed auroral and mid-latitude magnetometer stations. Most THEMIS stations supplement existing instrumentation at the proposed sites. Each THEMIS station includes a white-light All Sky Imager (ASI) and a ground magnetometer, both with time resolution of 1s. An auroral snapshot of a substorm onset by IMAGE is overlaid. The circles around the West-Alaska stations denote a typical ASI field of view. Burst data collection (according to local magnetic activity) renders ASI data collection manageable.*

f2. Macroscale Interactions

A THEMIS objective is to address how the localized, mesoscale substorm components interact over macroscale ranges:

In the context of the CD paradigm, THEMIS will measure the *tailward* motion of the rarefaction wave in δP, δB, δV, at speeds comparable to the local fast mode speed[90] (1600km/s). Probes P4 and P3 will first observe fast Earthward flows at onset, but P2 will not observe them until 20s later. P1 will observe no Rx signature until at least another 20-25s. *THEMIS probes P4, P3 and P2 will measure the outward motion of the rarefaction wave that links lobe flux dissipation to current disruption.*

In the context of the NENL paradigm, THEMIS will monitor the *Earthward* motion of the fast flows (typically[91] ~400km/s) by observing the anticipated >90s flow-onset time delay between P2 and P3 or P4. In the second year, probe P5u (see Figure D-6) at higher latitudes will determine if flow-driven boundary layer waves carry substantial Poynting flux. *THEMIS probes P2, P3 and P4 will monitor the Earthward flow and establish the link between current disrupt onset and reconnection.*

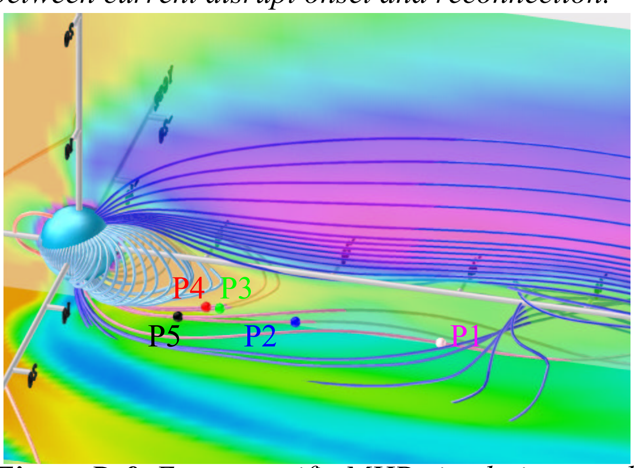

Figure D-9. *Event-specific MHD simulations model the substorm evolution in response to external conditions (probe colors same as in Figure D-6).*

Event-specific MHD and particle modeling. In the context of all paradigms, macroscale interactions will be modelled using event-specific MHD runs[92] driven by measured solar wind (Figure D-9). Additionally, particle modelling in prescribed **E** and **B** fields will validate[93] the outgoing rarefaction wave or the incoming flow hypothesis (Figure D-1/A_{IV}). *Using MHD and particle simulations THEMIS will strengthen closure on the macroscale interaction of components of the substorm instability.*

f3. Means of ionospheric coupling.

THEMIS will remotely infer (i) cross-tail current evolution and (ii) field aligned current generation. Studying 100-200 substorms, the mission will establish the macroscale coupling between the global substorm instability and auroral arc formation.

Cross-tail current reduction. THEMIS probes P4 & P5u will routinely straddle the current sheet at separations 0.2-1R_E and measure the cross tail current and its evolution (one to tens nA/m^2), using a planar approximation. Tail flapping due to solar wind buffeting[94], and diurnal effects[95] ensure multiple neutral sheet crossings. The cross-tail current modeled under worst case absolute δB noise from P4 & P5u data through an MHD run is shown in Figure D-1/A_{III}. The relationship to the incoming flows is simultaneously monitored by probe P2.

Additionally, the inner THEMIS probes will occasionally be away from the neutral sheet and will obtain magnetic field measurements across and along the tail. The current disruption process can then be remotely sensed with methods established on ISEE[23], and Interball[96]. Figure D-1/A_V shows such a reconstruction by THEMIS probes using simulated input of worst case noise amplitude.

Field aligned current generation. In MHD the field aligned current generated by the bursty flows can be due to[97,53,54] the flow vorticity, the flow braking, the radial pressure gradient or the cross-sheet pressure gradient. Pair conjunctions between probes P4, P3, P5f or P5u across the path of a (laterally expanding) flow channel or a (tailward expanding) pressure gradient will determine the *curl*V and *grad*P. For example, the vorticity modeled using worst case (~10%) detector noise as a flow channel moves past P4 & P5f in the context of an MHD run is shown in Figure D-1/A_{III}. Data from P2 during 100-200 substorms place the field aligned current generated in the global context.

The incoming flow interacts with Earth's dipole in a region of strong **B** field gradient and of high ion temperature. There, ion diamagnetic drifts become pronounced, and non-MHD effects are apparent. The splitting between the ions (drifting duskward) and electrons (which obey the plasma approximation, $V_e = E \times B / B^2$) calls for Hall MHD (hybrid) codes to model the observations and affects profoundly the generation of field aligned currents[57]. Such effects necessitate electric field measurements in addition to the ion flow data[29]. THEMIS will measure both plasma and the E×B flow independently and will be able to determine the (non-MHD) component of the ion drifts.

Event-specific hybrid modeling. Hybrid simulations in support of THEMIS design show (Figure D-1/A_{VI}) that probes P3 P4 & P5 can fully assess if the observed CD is due to electron acceleration (accompanied by flux transport) or due to an ion drifts reduction. *The THEMIS team will interpret its data on current wedge formation hand-in-hand with event-specific hybrid simulations.*

f4. Cross-scale coupling to local modes at 10R_E.

The substorm operates over a variety of coupled scale-lengths (Table D-4) applicable to all paradigms. Identifying these coupling processes is just as important to the substorm problem as identifying the local modes at play.

Ballooning modes. These have been identified by geosynchronous[98] and ionospheric[37] observations. Their free energy source is the near-Earth pressure gradient (1nPa/R_E). The modes have wavelengths $\lambda=2*\pi*\rho_i$~2000-12000km, move azimuthally at the ion drift speed (50-100s of km/s) and have a Doppler-shifted ($\omega=V_d*k_y$) period T~0.3-2 min. Coherent waves are expected on spacecraft traversing the near-Earth region at the (~1R_E^2) onset location[99]. Classical ballooning is near marginal stability for typical tail parameters[100,101]. This has led to non-linear ballooning mode theories[102], and linear but absolute instabilities[103].

Scale	Size (R_E)	Process
Macro	10	Rx/CD coupling. Current Wedge formation. Field line resonances.
Meso	1	CD onset size. Ballooning modes. Kelvin-Helmholz waves.
Micro	0.1	Cross-field current instabilities. Aflven waves.

Table D-4. *Scales of processes at substorm onset.*

An alternative approach, the shear-flow ballooning, suggests that ballooning is part of a larger cross-scale coupling process[10,104]. It proposes that field line resonances[105] (λ~2-10R_E, T~5min) drive Kelvin-Helmholtz (KH) waves (λ ~0.2-1R_E) which in turn become non-linearly unstable within ~1min. KH waves drive smaller (δY~0.1 R_E) Alfvenic currents dissipating energy through the ionosphere. The (East-West) cross-field flow shear driver has δV~200km/s; the waves have phase speeds V_ϕ ~50km/s. Independent Poynting vector calculations show[106,107] the bouncing Alfven waves, but their association with ballooning is not confirmed.

Ballooning modes and resonances will be apparent on THEMIS probes as coherent waves in cross-tail pairs P4 and P5f, and will be studied using cross-spectral, wave-telescope[108] and Poynting vector techniques. Phase speeds measured using probe pairs will be compared to flow speeds measured on both probes. Using cross-tail probe pairs (P4 & P5f) at separations of 0.3-10 R_E THEMIS will identify the properties of the ballooning mode waves. MHD simulations will be used to model observations[104]. Coupling to the global substorm instability is simultaneously monitored by P2.

Cross-field current instabilities. These are driven unstable when the cross tail current exceeds an instability threshold[16] (10 nA/m^2, or 100 mA/m). They have frequencies 0.01-0.1 f_{LH} (f_{LH}, the low hybrid frequency is 60Hz at 8R_E), wavelengths 300-2000 km and exhibit no cross-tail spectral coherence. THEMIS's **E** and **B** field instrument data and their phase relations will identify the unstable wavevector direction and mode. Cross-tail probe pairs (P4 & P5f) will ascertain the lack of spectral coherence. Particle-in-cell simulations[109] will establish if the observed wave amplitudes and particle streaming compare favorably with non-linear saturation amplitudes of the unstable modes. Again, P2 monitors coupling to the global substorm process.

THEMIS probe P2 along with pairs of P3, P4 and P5f, P5u determine during 100-200 substorm events the local mode type, free energy source and cross-scale coupling to the global substorm.

g. Additional tail science.

THEMIS can contribute towards understanding other important phenomena indirectly related to substorms. These goals are not primary mission goals and do not drive the mission design.

Flux-tube evolution along streamlines. Adiabatic[110] convection does not match the average lobe pressure profile[111] resulting in a "pressure balance inconsistency". Bubbles generated by uneven density loading in the tail[112] and propagating rapidly Earthward[113] have been proposed as the solution to this crisis, but their observations are limited to late substorm recovery[30]. Is the bubble evolution applicable to all fast Earthward moving flux tubes? *THEMIS probes P4/P3, P2 and P1 will determine the flux-tube evolution of fast flows along their streamlines and their importance in resolving the pressure balance inconsistency.*

High frequency modes. Waves in the Pi1 pulsation range[114] or beyond[115] exist during substorms. They may be driven unstable by low energy [0.5-2 keV] electrons[116], or by free energy sources due to the kinetic structure of a thin plasma sheet[117]. Bursty and broadbanded they extend to f~4*f_{LH} about 10-20% of the time. They are occasionally (1/5 of the time) accompanied by whistlers at 1-10*f_{LH}. Burst waveform collection of **E** and **B** data up to 10*f_{LH}, or 600 Hz (f_{LH}~60Hz at 8R_E) on *THEMIS will identify these modes, and place them in the context of substorm evolution.*

h. Radiation Belt (Secondary objective).

At storm main phase, MeV energy electrons are abruptly (1-4hrs) lost; they reappear also abruptly at storm recovery with fluxes higher than prior to the storm (Figure D-10). This MeV electron flux increase represents the main electron flux increase of electrons during a storm.

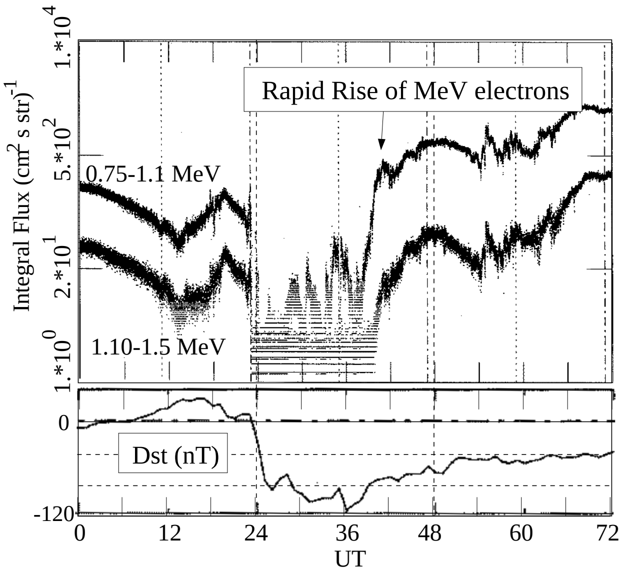

Figure D-10. *LANL satellite data on November 3, 1993 storm exemplify the rapid loss and reappearance of storm time electron flux at geostationary orbit at storm onset and rapid (1-4 hr) reappearance at recovery*[118].

The observed *rapid* increase of MeV electron flux inside of geosynchronous altitude cannot be accounted for by the *relatively slow* diffusion of solar wind plasma. The "Dst effect" *alone* cannot account for this process either, since the electrons reappear at much higher fluxes than before the storm. Electron fluxes are therefore likely enhanced at L=11 before being transported inwards. Daily variations of MeV electrons are modeled successfully under that assumption[121], but it is unclear whether such an electron source is indeed present beyond geosynchronous altitude at storm recovery.

The instantaneous radial profile of the electron flux at constant μ and the transport process fully determine the evolution of the outer belt. But no single satellite traversing the equatorial radiation belt and its sources (i.e., L-values from 3.5 to 11) can measure the radial profile of the electron fluxes faster than once per ten hours, due to its orbital period. Low altitude (polar) satellites measure near-loss-cone fluxes and underestimate the true equatorial flux value which peaks at 90^o at active times. Multiple, eccentric, equatorial satellites are needed, displaced sufficiently along their orbit to provide repetitive cuts through the radiation belt. MMS spacecraft are too closely spaced for such a task; they will move together through the belt region.

THEMIS probes traverse the inner magnetosphere from L=3.5 to L=11 with a median recurrence rate of 3.8 hours. Thus, *THEMIS will determine the radial profile of the electron phase space density at constant* μ, *on a time scale commensurate with the storm-time radiation belt MeV electron loss and re-appearance.* Based on the slope of the obtained flux profiles with L-shell, *THEMIS will determine whether there is a sufficient source of electrons at the outer boundary.* If the answer to this question is affirmative, THEMIS will identify the primary transport mechanism. The Dst-effect will be readily evaluated from individual radial flux profiles. The radial diffusion coefficient will be obtained from first order differencing of consecutive profiles while the plasma convection will be directly measured on each probe. *If radial transport alone cannot account for the MeV electron enhancement*[122]*, THEMIS, equipped with comprehensive fields instrumentation, will determine whether other proposed mechanisms (e.g., waves) are responsible for local electron heating.*

Finally, THEMIS's ground observatories and its tail flow monitor P2 along with the radiation belt monitors P3, P4 and P5 promise to advance our knowledge on storm-substorm[123] relationships.

i. Dayside (Tertiary objective).

Observations near the equatorial magnetopause provide strong evidence for the predicted signatures of transient solar wind-magnetosphere coupling, namely fast flows[124] and flux transfer events (FTEs)[125]. These may be either triggered by solar wind features[126] or occur in response to intrinsic instabilities[127]. A number of other externally driven transient phenomena also contribute to the variations observed on single spacecraft. *Efforts to discriminate between the causes of magnetopause transients and determine the significance of each phenomenon to the solar wind-magnetosphere interaction have been hampered by several obstacles:*

First, observations near the L1 point or several 10s of R_E off the Sun-Earth line are of limited use because solar wind features transverse to the Sun-Earth line are on the order of ~20 R_E[128,129] and lag time uncertainties increase with distance[130].

Second, foreshock and magnetosheath processes affect the magnetopause. These cannot be observed within the pristine solar wind[131,132] (Figure D-11) and must be observed in place. Examples are: Hot flow anomalies transmitted across the bow shock[133,134] and sheath[135,136]; externally-driven, propagating slow shocks[137] or standing slow shocks[138] in the magnetosheath.

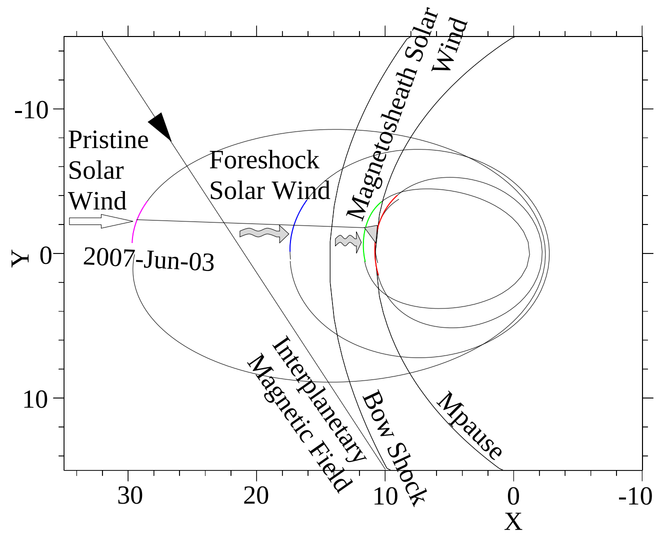

Figure D-11. *Same as in Fig. D-5 but for the dayside equatorial magnetosphere.*

Third, the significance of individual events depends upon their azimuthal dimensions. FTEs range from 0.5 to 5 R_E[139]. Events with similar features include solar wind/foreshock pressure-driven waves[140] or Kelvin-Helmholtz[141] waves.

Thanks to its unique Sun-Earth aligned probe conjunctions (Figure D-11), THEMIS will overcome the aforementioned obstacles and decisively determine the response of the coupled dayside solar wind-magnetosphere system to varying incident conditions. With particle and magnetic field instrumentation similar to that flown on AMPTE/IRM, THEMIS probes P1 and P2 will not only characterize the solar wind but also will determine its modification within the foreshock. As in previous case studies[135,140], we will use the ion plasma instrument to determine solar wind velocities and the electron plasma instrument to determine densities and temperatures. Hundreds of hours of simultaneous conjunctions will enable us to conduct statistics of event occurrence patterns and characteristics as a function of the solar wind conditions.

Probes P3 and P4 will discriminate between standing waves and time-dependent shocks propagating through the sheath in response to upstream features measured by P2. Probe pairs P4 & P5f, monitoring the magnetopause over scale sizes from 0.5 to 6 R_E will determine the propagation direction, speed and azimuthal dimensions of transient events. Aided by global MHD modeling the THEMIS team will use simultaneous magnetosheath (P3), and solar wind (P2 and P1) observations to determine the ultimate triggers of events along the streamlines. The combination of P4 and P5 at 10R_E, along with P3 at 12 R_E will validate previously used remote sensing techniques (e.g., Walthour et al.[142]) and enable a systematic survey of transient events at the magnetopause, in both THEMIS's and in previous datasets. Thus, *THEMIS will establish the nature, cause and extent of magnetopause transient events.* Whereas MMS and CLUSTER will define the internal structure of individual magnetopause reconnection events, *THEMIS will provide the context in which they occur, identify the trigger (if any), and determine their significance to the solar wind-magnetosphere interaction.*

j. The Need for the Investigation in Light of Past, Present and Future missions.

Past missions. Rare, fortuitous spacecraft alignments have led to contradictory answers because of unoptimized satellite locations or inadequate instrumentation[34].

Present missions. CLUSTER due to its orbit cannot study the equatorial region where auroras map (10R_E, nightside plasma sheet). Upcoming tail-aligned conjunctions between POLAR (9R_E) and CLUSTER (19R_E) are limited to <27hours, only in 2003 (δMLT>1.5hours in other years) due to the different precession of the orbits; for those POLAR does not provide multi-point measurements at 9R_E.

Relationship to MMS. While THEMIS makes the macroscale measurements necessary to study the substorm instability, MMS will be making the micro- and meso-scale measurements to address physics of plasma boundaries, in general, and magnetic reconnection in particular. As evident from Figure B-2 THEMIS is complementary in scale-size and temporal resolution to MMS's planned 3-month survey of the 10R_E magnetotail region[144]. There MMS will advance our understanding of some of the micro/meso scale phenomena involved in the substorm process from complementary scales to THEMIS's macroscale vantage point. However, there is no provision in MMS for a simultaneous downtail monitor that would place these in a global substorm context. While MMS studies reconnection at 25R_E, THEMIS does not visit that region locally and aims at remotely sensing Rx onset time to identify the role of lobe flux dissipation in substorm onset. Only one of many candidate substorm models advocates that Rx is the trigger of substorms (NENL), while all others advocate that Rx is either an immediate effect, or a parallel independent process. In summary MMS and THEMIS are independent, self-sufficient and fully complementary.

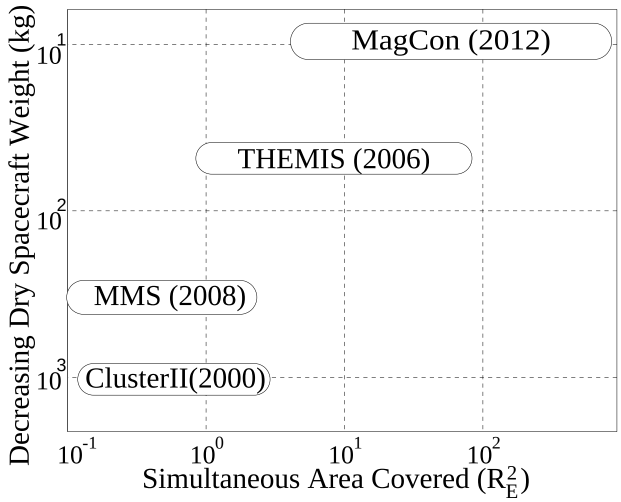

Figure D-12. Evolutionary process of SEC missions. THEMIS expands SEC's capability to effectively monitor simultaneously an increasing volume of space. While utilizing existing technologies it provides a much needed heritage for microspacecraft design, deployment and operations.

Future missions. MMS cannot address the substorm onset, global evolution and cross-scale coupling problem because it lacks the large baseline measurements needed. The Magnetospheric Constellation mission is expected to study global transport phenomena (including substorms) over a range of scales similar to THEMIS, but will lack the complete instrumentation afforded by a small fleet of satellites and necessary to link local instabilities to global interactions. THEMIS's unique science goals and mission design presents the only viable candidate for resolving the important substorm problem. THEMIS is an evolutionary step between Cluster / MMS and MagCon (Figure D-12).

k. History and Basis for the Proposal.

The THEMIS team has been improving its observation strategy since 1996. It originally proposed a UNEX mission (QUATRO) with minimal instrumentation and a piggyback launch. It received excellent science reviews but was deemed inappropriate for the UNEX category. The mission was proposed under a SMEX opportunity as a dual-launch on a Delta-II. It received excellent technical evaluation but the instrumentation suffered from a one-dimensional electric field measurement. The major and minor recommendations of the SMEX proposal can only be addressed adequately with a MIDEX class mission. More specifically: 1) THEMIS probes now are equipped with 3 dimensional electric field sensors. The measurement is aided by a phasing of the prime mission (tail investigation) during winter solstice over the North American sector. At such times the dipole tilt is large and even under extreme plasma sheet thinning conditions the magnetic field is at a large (>30^o) angle to the spin plane (ecliptic). At all times the traditionally elusive spin axis component of the DC **E**-field can be accurately inferred at P3, P4 and P5 also from the spin plane components. 2) The same orbit phasing responds to a recommendation for ground onset determination. 3) A recommendation to directly monitor the Rx process simultaneously with the CD region is addressed by bracketing the Rx site with THEMIS probes P2 and P1. The MIDEX AO permits a comprehensive science implementation, a high reliability approach, a dedicated launch vehicle, and a fault tolerant mission design.

g. Baseline mission overview.

THEMIS will achieve its goals in two years using five identical spacecraft (<u>*probes*</u>) routinely measuring in-situ the electric and magnetic fields at 32 vectors per second and ion and electron distributions once every three seconds (spin period). The five probes will be placed in near-equatorial, highly eccentric orbits with apogees between 10 & 30 R_E.

Choice of orbit. The orbit strategy follows naturally from the requirements of Section D1.e. Probes are tabulated in Figure D-1/B_{III}. Probes P4 and P3 have apogees at 10R_E and 12R_E and have the same mean anomaly. The third innermost probe (P5f, or fast) has also an apogee of 10R_E but during the first year it has a faster-than-synchronous period, gaining 7min/day along is orbit relative to P4. Cross-tail separations between P4 and P5f range between 0.3 and 10 R_E permitting the innermost probes to monitor longitudinally the lateral expansion of the substorm current wedge and monitor local instabilities from the MHD to the kinetic regime. During the second year the third innermost probe has the same period (24hrs) and mean anomaly as the other innermost probes but a slightly higher inclination, such that the two innermost probes are separated primarily in the north-south dimension by 1R_E at apogee (down to 0.1 R_E at other interesting locations). This permits studies of the thin cross-tail current during substorms. Fine-tuning of mean anomalies and periods prior to each science phase (tail, dayside) maximizes conjunction number and duration.

Measurements. The primary science objectives call for 3D measurements of thermal ions and electrons at 3s resolution, and magnetic and electric fields at 12vectors/s resolution. Additionally superthermal ions and electrons along the spin plane are required, for CD and Rx timing. Sensitivity should permit differential measurements of average cross-tail current, pressure gradients and flow vorticity to within 10%. Since inter-probe distances are planned to be comparable to the variation scale-lengths of B ($0.5R_E$ in Z), P and V ($1R_E$ in X,Y) the plasma moments and magnetic field should be known to within 10%. This accuracy can be easily achieved by instruments flown on previous missions. THEMIS instruments are shown in Figure D-13. Requirements and adherence to them are summarized in the table inserts.

h. Baseline versus minimum mission.

THEMIS depends on four tail-aligned probe conjunctions and on cross-tail or cross-sheet probe pairs to address its main question. Science closure can be achieved by a minimum mission of four probes, in three years of tail crossings (Figure D-1/A_{II}). Inclusion of a fifth probe in the baseline mission reduces the required lifetime to 2 years, reduces risk and increases science return. Lower risk comes from the fact that the fifth probe has sufficient fuel reserves to replace any other probe during the mission. Science increase from the fifth probe allows two-probe measurements in both X and Y dimensions the first year (X and Z dimensions the second year). Additionally, THEMIS's primary science can be achieved, in principle[145], with a 3D, fluxgate magnetometer and a 2D, spin-plane, electric field measurement. The increased sensitivity of the SCM in the range of ~10Hz and above, and the robustness in mode identification through a 3D EFI experiment are descopes of the baseline mission.

D2. SCIENCE IMPLEMENTATION

The five spin-stabilized (T_{spin}=3s) probes carry identical instruments which exceed the requirements of the primary science objective. The guiding principles are: 1) Selection of existing, low power, low weight units, to ensure no new development costs. 2) Common instrument DPU (IDPU) electronics to maximize science and simplify interfaces, motivated by FAST. 3) "Common buy" parts procurement to minimize expenditures. 4) Significant foreign contributions in instruments and analysis, ensuring wide international community participation. 5) Rapid, web-based dissemination of data and IDL analysis code accompanied by a $4M guest investigator program to ensure maximum benefits for the US science community.

a. Instrumentation

THEMIS instruments are summarized in Table D-5. Detailed specifications and accommodation are provided in Figure D-13. The five high-heritage instruments are identical (or require minor modifications) to ones flown recently. Two of those (FGM, SCM) are provided by foreign institutions, two by UCB (EFI, ESA) and one is a collaboration between UCB and a foreign institution (SST). THEMIS builds on existing close working relationships of its team members with each other and/or with UCB on Cluster, WIND, FAST, POLAR and Equator-S.

Instrument	Mass (kg)	Power (W)	Recent Flight	Institute
FGM @ sensor	0.1	Equator-S		TUBS
FGM boom	1.2		FAST	UCB
FGM @ DPU	0.2	0.6	MIR	IWF
ESA @ sensor	2.1	2.0	FAST	UCB
ESA @ DPU	0.2	0.6	FAST	UCB
SST @ sensor	0.9	0.8	WIND	UCB, ESTEC
SST @ DPU	0.1	0.2	WIND	UCB
SCM @ sensor	0.6		Cluster	CETP
SCM boom	0.5	Lunar Prospector		UCB
SCM pre-amps	0.2	0.1	Cluster	CETP
EFI (4) @ spin-plane	7.0	2.0	Cluster	UCB
EFI (2) @ axials	4.0	1.0	POLAR	UCB
EFI/SCM @ DPU	1.2	3.8	FAST	UCB
DPU process, compress & store	1.1	1.1	FAST, Lunar Prospector	UCB
Total	19.3	12.2		
Available	25.1	15.9		
Margin	30%	30%		

Table D-5. *Summary of each probe's instrument characteristics.*

a1. Fluxgate magnetometer (FGM)

A triaxial fluxgate magnetometer built to the heritage of units flown on AMPTE/IRM (1985), Phobos (1988), Interball (1992), Equator-S (1997) and MIR (1998) will measure the 3D ambient magnetic field. The sensor and electronics are identical to ones of the ROMAP instrument package delivered for the Rosetta mission (launch 2003), and similar to the ones flown[146] on Equator-S and MIR. The sensors will be built by TUBS, and the electronics breadboarding will be performed by IWF. The same team has delivered the ROMAP unit and has the expertise, and established working relationships to perform the task seamlessly. The flight electronics will be implemented at UCB. In-flight calibration will be performed by UCLA, deriving from Galileo and CLUSTER practices. The science requirements are to: 1) Measure DC and low frequency perturbations of the magnetic field, 2) Time