THEMIS-MMS coordination: The makings of a Heliophysics System Observatory and the beginning of a new era in our understanding of global connections

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NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

Research Recommendations

Baseline Priority for NASA and NSF: Complete the Current Program

The survey committee’s recommended program for NSF and NASA assumes continued support in the near term for the key existing program elements that constitute the Heliophysics Systems Observatory (HSO) and successful implementation of programs in advanced stages of development.

NASA’s existing heliophysics flight missions and NSF’s ground-based facilities form a network of observing platforms that operate simultaneously to investigate the solar system. This array can be thought of as a single observatory—the Heliophysics System Observatory (HSO) (see Figure 1.2). The evolving HSO lies at the heart of the field of solar and space physics and provides a rich source of observations that can be used to address increasingly interdisciplinary and long-term scientific questions.
Orbits on XY GSE plane at MMS launch date

MMS nominal launch for Mar 15, 2015 (RpxRa=1.2x12 Re, inc=28°): Line of apsides inertially drifts: 25.3deg/yr counter-clockwise.

THM on Mar 15, 2015 (RpxRa=1.1x12.1 Re, inc=8°) Line of apsides inertially drifts: 44°/yr counter-clockwise.
Motivation for an optimized Heliophysics System Observatory

• Recent findings show that dayside reconnection-driven activations are responsible for fast anti-sunward-moving ionospheric flows.
• When the corresponding magnetospheric flows reach the plasma sheet, they can trigger nightside reconnection, initiate substorms, inject particles, and generate fast earthward flows.
• Fast flows from the tail result in ion and electron injections into the inner magnetosphere that build up the ring current and the radiation belts.
• Consequently, magnetic reconnection on the dayside and nightside are intimately inter-connected by meso-scale (azimuthally localized, 1-3$R_E$) flows.
• Fortunately, these can be imaged through the motion of polar cap patches, and measured by ground radars. Optical observations are best at 0-12UT (North).
• By placing THEMIS and MMS at apogee simultaneously at the day/night side, we are able to optimize the global observations of the magnetosphere, provide context for VAP, ERG and other missions, and understand global drivers and effects of magnetic reconnection.
• This is an unprecedented opportunity to optimize the Heliophysics Fleet.
Motivation: Dayside plume affects Rx rate, and results in polar cap patches.

Control of dayside reconnection by emergent plasmaspheric plumes

SW driving: weak

SW driving: strong, repelled

plume $\rightarrow$ polar cap patches

Borovsksy, Science, 2014

Nishimura, et al., 2014

Walsh, Science, 2014

HSO optimization
Magnetotail reconnection (Rx) leads to fast flows, that cause auroral “streamers”.

Tail dissipation sequence: Reconnection (Rx) initiates flows, injections, substorm onset.

ARTEMIS + THEMIS demonstrated that those tail flows are driven by reconnection and are the dominant location of magnetic –to-kinetic energy conversion in the tail. Thus they are critical to understanding the consequences of reconnection.
Fast flows affect inner magnetosphere by creating injections and waves

Streamer driving proton aurora (dusk)  Streamer driving pulsating aurora (dawn)
THEMIS ASIs
21 cameras covering a large section of the auroral oval.
Latitudinal coverage ~9°.
Longitudinal coverage ~2.5 h MLT. Temporal resolution of 3 s
Subauroral Polarization Streams, and other space weather phenomena

One event

Uniform flows

Westward flow enhancement

Proton aurora intensification

00:45:00 01:22:15 01:24:00
Subauroral Polarization Streams, and other space weather phenomena

Uniform flows

Westward flow enhancement

Proton aurora intensification

2013-03-30

00:45:00

01:22:15

01:24:00
(One) Goal: To understand global transport of energy, magnetic flux and particles by meso-scale activations. Excited by dayside reconnection and possibly driving nightside reconnection, these activations are elemental transport processes transcending the old paradigms for magnetospheric convection modes (storms, substorms, steady convection). Going beyond ISTP, which employed isolated single probes to establish global connections on longer time-scales, the nascent HSO builds upon an emerging paradigm of global coupling through transient, regional flows towards a deeper understanding of how regional plasma physics processes are affected by and, in turn, drive global connections.

Methodology: To measure kinetic processes resulting in meso-scale flows at the key regions of energy conversion and understand their global coupling. To understand the dayside-nightside coupling and the dawn-dusk asymmetries of sources and sinks of particles, waves and energy with a coordinated, global constellation of spacecraft clusters.

Strategy: As a minimum: Ensure THEMIS and MMS spacecraft are simultaneously both at apogee or provide coordinated radial profiles of the magnetosphere (day-night or dawn-dusk). Use existing polar cap imagers to detect and track polar cap flows moving from dayside to nightside. Tune THEMIS separation and orbit-phase according to position of MMS, Van Allen Probes or GBOs. If possible: tune THEMIS/MMS fleet phasing for optimal utilization of auroral observatories to provide contextual information of multiple nightside activations.
THM/ART-MMS-VAP in FY16
THM-MMS are period-locked in Phase 1a;
P5 becomes MMS-resonant in Mar. 2016

MMS Dayside #1 (THM in Tail)  
(MMS Phase 1a, Dec. 16, 2015)  
THM detects tail bursts,  
connects injections to VAP

MMS, THM at Dawn or Dusk opposite  
each other (Mar. and Sep., 2016)  
Coordinated L-shell crossings determine  
particle sources and wave contribution to  
inner m’sphere particle flux growth/decay

MMS Tail #1 (THM at dayside)  
(MMS Phase 1x, Jun. 29, 2016)  
THM studies dayside Rx; MMS at  
the plasma sheet boundary studies  
flux transport (using EDI instrument); connects to VAP

THM-MMS resonances:  
P3,4:MMS = 1:1 \([P3,4 \times R = 12.1 R_E]\)  
P5:MMS = 8:7 \([P5 \times R = 13.2 R_E]\) (except in Phase 1a where P5 is as P3,4)  
At all times at least two THEMIS spacecraft are in-phase w/MMS  
P5 scans all separations (lap period = 8 days) and is a link to VAP
...in FY17: THM period-locked or resonant w/ MMS in Phase 1b; resonant in Phase 2b

MMS Dayside #2 (THM in Tail) (MMS Phase 1b, Jan. 12, 2017) THM detects Rx fronts, electron injections, links to VAP's waves

MMS, THM at Dawn and Dusk respectively (Apr. 19, 2017). MMS in ascend phase (1x) L-shell crossings determine particle sources and wave contribution to inner m'sphere particle flux growth/decay

MMS Tail #2 (THM at dayside) (MMS Phase 2b, Jul. 22, 2017) THM and MMS study dayside and nightside Rx simultaneously; VAP determines geoeffectiveness

THM-MMS period resonances during Phase 2b:
P5:MMS = 5:2 [P5 $R_A=13.2R_E$] (For every 5 orbits of P5, MMS has 2)
P3:MMS = 6:2 [P3 $R_A=11.5R_E$]
P4:MMS = 11:4 [P4 $R_A=12.3R_E$]
Every 2 MMS orbits P3 and P5 are at apogee while MMS is too
Every 4 MMS orbits all 3 THEMIS spacecraft are at apogee
At all times at least one THEMIS spacecraft is near m’pause
THM/ART-MMS-VAP in FY18. P3,4,5 at resonant orbits w/GBOs or w/MMS.

MMS Dayside #3 (THM in Tail) (Feb. 12, 2018)
THM on sidereal period resonances, together with GBOs studies Rx fronts, injections, links to VAP;
MMS studies drivers of m’pause boundary layer flows.

MMS, THM at Dawn or Dusk respectively (dashed: Dec. 2017; solid: May 2018).
In both, THM is on MMS-resonant orbits. THM-MMS explore asymmetries of Rx, and
drivers of m’pause boundary layer flows.

MMS Tail #3 (THM at dayside) (MMS “extended-tail”, Aug. 29, 2018)
THM-MMS on resonant orbits, study dayside-nightside Rx simultaneously.

THM on sidereal period resonances (8:4:1):
$T_{P4} = 1 \text{ day} \ [P4 \ R_A=12.1R_E]$
$T_{P5} = 8/7 \text{ day} \ [P5 \ R_A=13.2R_E]$
$T_{P3} = 4/3 \text{ day} \ [P3 \ R_A=15.8R_E]$
Two or three THM-GBO conjunctions (once per 4 or 8 days)
explore the dominant energy conversion in the tail and the drivers of nightside reconnection, while MMS captures the global drivers of these phenomena at the dayside.
VAP-THM jointly study effects in inner magnetosphere.

THM @ Dawn, Dusk and Dayside is in resonance with MMS
Dawn as in FY17. THM @ Dusk and Dayside resonances are:
P4,5:MMS = 5:2 \ [P4,5 \ R_A=13.2R_E] 
P3:MMS = 2:1 \ [P3 \ R_A=15.5R_E] 
Every time MMS is near apogee P3 is too.
Every 2 MMS orbits P4,5 are also at apogee.
... in FY19: THM at resonant orbits w/ GBOs or MMS.

MMS Dayside #4 (THM in Tail) (Mar. 30, 2019)
THM studies dominant energy conversion further out in m’tail, as ART+MMS provide the high-fidelity solar wind and its variations due to foreshock interactions. Near perigee, MMS studies effects of injections.

MMS, THM at Dawn or Dusk respectively (dashed: Jan. 2019; solid: Jul. 2019). As in FY18, but explore asymmetries over a wider swath of m’pause.

MMS Tail #4 (THM at dayside) (MMS "2nd extended-tail", Sep. 3, 2019)
THM-MMS on resonant orbits, study dayside-nightside Rx simultaneously.

MMS’ P5’ ERG

THM on sidereal period resonances (8:4:1):
T_{GBO} = 1 day
T_{P5} = 8/7 day [P5 R_A=13.2R_E]
T_{P3,4} = 4/3 day [P3,4 R_A=15.8R_E]
Two or three THM-GBO conjunctions (once per 4 or 8 days) explore the dominant energy conversion in the tail and the drivers of nightside reconnection, while MMS captures the global drivers of these phenomena at the dayside.

THM @ Dawn, Dusk and Dayside is in resonance with MMS
Dawn is as in FY17. THM @ Dusk and Dayside resonances are:
P5:MMS = 5:2 [P5 R_A=13.2R_E]
P3:MMS = 2:1 [P3 R_A=15.5R_E]
Every time MMS is near apogee P3 is too.
Every 2 MMS periods P5 is also at apogee.
P4 is on same period as P3 at night & dusk but as P5 elsewhere.
...FY20: THM at resonant orbits w/MMS or GBOs 
→ THM clustered at 13.2\,R_E (Feb. 2020).

THM @ Tail (MMS at Dawn) 
(May. 9, 2020)

THM-MMS study the dominant energy conversion in the tail from kinetic scale separations while MMS studies link to inner m’sphere.

THM, MMS both at dusk (dotted: Oct. 2019) 
MMS, THM both at dawn (dashed: Jan. 2020)

Evolution of Rx and its relationship to growth of low-latitude boundary layer instabilities, such as Kelvin-Helmholtz.

MMS @ Tail (solid: Sep. 8, 2020).
THM is an MMS-resonant string-of-pearsls studying connections to both m’pause and inner m’sphere.

THM – MMS on resonant orbits (5:2):
P5:MMS = 5:2 [P5 \, R_A=13.2\,R_E]
Every 2 MMS periods, when MMS passes through its in- or out-bound leg, THM is near apogee or inbound leg.
From its kinetic-scale separations THM explores the dissipation of flow and magnetic energy in the tail while MMS captures their effects in the inner magnetosphere.

THM-MMS@Dawn resonances with MMS are as in FY19 
(5:2 for P4,5 and 2:1 for P3).
MMS @ Tail resonances are as in FY20 THM@tail 
(5:2 for all P3,4,5). Once every other MMS orbit, MMS is at Rx point and THM is at m’pause to capture day/night connections. The other MMS orbit THM is at in-bound leg (string of pearls) studying link of Rx/injections to inner magnetosphere over a wide range of L-shells.
Ground based asset coordination: Working with the GEM and CEDAR communities on the planned HSO conjunctions (dates, configurations) to optimally plan ground assets to coordinate with spacecraft fleets. The following assets would be important in addition to the THEMIS/GBOs and existing multi-spectral imagers: AGOs, NSF ISR radars, SuperDARN etc. Special “HSO” modes of operation might benefit our understanding of global connections.
HSO ENHANCEMENTS:

National and international space programs: An optimized HSO provides the framework for other missions (e.g., NOAA/GOES and POES, JAXA/ERG). Small satellites (e.g., cubesats) can be built to fill “holes” or answer targeted questions in this greater network. The existing, planned and potential future missions can augment the program quite significantly. The community at-large would benefit from a pro-active NASA stance on the opportunities that lie ahead.

Joint data analysis tools: Analysis tools that integrate multiple satellites can optimize the science return in the new era. Existing resources or planned (future) calls for data analysis tools or data enhancements can be geared in that direction.

NASA Heliophysics Theory: The HSO can provide the focal point for concerted efforts to understand, at a deeper level, the fundamental questions of energy and mass transport across geospace, first raised during the ISTP era. Recent findings suggest that coupling of kinetic and global processes occur through regional, meso-scale flows. Understanding how such coupling occurs cannot be accomplished by one type of code in one region of space, but by research teams under a coordinated theoretical program. Existing resources or planned (future) calls could be geared in that direction.
SPEDAS: intro., analysis, communication tool, including SPDF data

SPEDAS plug-ins: THEMIS, ERG, VAP (2), BARREL, SuperDARN, GOES, POES, MAVEN, WIND...

http://spedas.org/
By putting the available THEMIS fuel resources and collaborating with MMS we can coordinate Heliophysics existing and future assets towards an optimized HSO. We not only answer critical questions regarding cross-scale coupling in geospace but can also provide a framework to organize national and international teams of ground based and space based platforms to contribute towards an international HSO platform.

We think this coordinated action will usher a new era of understanding of global connections through kinetic and meso-scale processes, and motivate the new generation of researchers as well as space missions.

This new era of enlightenment would not be as rewarding if we rely on fortuitous conjunctions alone and if ground based resources remain un-coordinated.