Magnetospheric Constellation (MagCon)  
Decadal Survey Mission Concept Studies  
Pre-Study Report  

Science  
One can broadly categorize plasma regimes into three scales: microscale (kinetic), mesoscale, and global or macroscale. At the smallest scale, kinetic physics deals with the motions and effects of individual particles. Dynamics in this regime include thin current sheets and magnetic reconnection, wave-particle interactions, kinetic plasma instabilities, and particle acceleration. The temporal and spatial scales are dictated by particle gyromotion. At the opposite end of the spectrum, macroscales are defined as significant fractional sizes of the system under consideration, and the timescales associated with global spatial scales are determined generally by the timescale it takes to significantly alter the global structure. In between lies the mesoscale, which is the fundamental link for the multi-scale, bidirectional feedback between micro and macro because it serves as a conduit for mass and energy flow. Though each regime encompasses vastly different temporal and spatial scales, the bidirectional feed-back across the scales is crucial to physical understanding and, ultimately, prediction.  

Within Earth’s magnetosphere, we have measured the microscale extensively (MMS, Cluster, Van Allen Probes), and the global (ISTP and the HSO), at least in an average sense. These missions and programs have been revolutionary. Yet, as we argue below, there still remain a large number of unanswered, fundamental questions about how the magnetosphere processes mass, momentum and energy from the interaction with solar wind. What we learned from ISTP and follow-on missions, and what the numerical simulations are hinting at, was that we must resolve the scales of energy transport if we are to make further progress. The next step in understanding magnetospheric dynamics is to explore the mesoscales, the intermediate scale in between the kinetic and global, which is a fundamental size scale of mass, momentum, and energy transport, and the weakest link in our chain of understanding.  

THEMIS has highlighted that the near-Earth transition region is a critical region for study. It is here that flow bursts are braked and deflected, and flux pile-up and dipolarization occur; where particles are rapidly energized and injected into the inner magnetosphere; and where strong field-aligned currents couple the ionosphere to magnetospheric drivers. On the dayside and flanks, there are still open questions about the nature of solar wind coupling – e.g., is it controlled by local conditions? – and a lack of quantitative understanding of dayside energy transfer. The limiter has been our inability to study the mesoscales, because it requires either high spatial and temporal scale imaging of geospace (currently impossible for the tenuous magnetotail) or constellations of spacecraft.  

Our targeted knowledge gaps are split between energy input and energy transport, storage, and release, and are listed in Table 1.
### Flow of mass, momentum and energy through Geospace

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*These questions are fundamental to solar wind-magnetosphere interactions, and unless we can quantify the answers to these open questions, further progress on understanding Geospace as a system will be limited.* Indeed, some of these questions are so fundamental to solar wind-magnetosphere interactions, that it is surprising they are still unanswered. It has so far been impossible to close on these questions because events in the magnetosphere occur on multiple scales, from a few 100 km to the system scale size, from the microphysics of dipolarization fronts, to mesoscale flow bursts, to the macroscale, integral effects of mesoscale flow bursts and instabilities within the transition region. *Single point or tightly clustered in situ measurements have been wholly incapable of understanding the multiscale dynamics that is central to the magnetospheric response to solar wind driving, and our lack of knowledge about the mesoscales is the greatest impediment to progress.*

**Science Goal 1: Energy input**

The magnetopause boundary, both at the dayside and flanks, is the site where solar wind flow energy is transferred into Earth’s magnetosphere. Magnetic reconnection is believed to be the dominant mechanism of energy transfer during southward IMF, yet we do not know the temporal or spatial scales of reconnection. Other coupling mechanisms, including the Kelvin-Helmholtz instability and diffusion induced by wave-particle interactions, provide additional mass and energy transport across the magnetopause boundary. In addition to fundamental questions
regarding the interaction, we still lack a basic quantitative understanding of energy transfer into the magnetosphere. The best coupling functions are able to account for only 70-80% of the observed energy input, suggesting major gaps in our understanding of the coupling. Substantial questions regarding the input and transfer of energy into the magnetosphere remain. Single point or narrow clusters of observations remain inadequate to the task of understanding when, where, and under what conditions the different modes of energy input occur, or for quantifying the significance of individual modes to the overall interaction.

Objective 1a. Determine quantitatively the extent and temporal evolution of magnetopause reconnection

We have known for decades that a southward component of the solar wind’s interplanetary magnetic field enhances the likelihood of reconnection on the dayside magnetopause. Every modern solar wind coupling function has a term, \( L \), for the width of the geoeffective area along the magnetopause (i.e., length over which the solar wind’s electric field maps to the reconnecting magnetopause). To quantify the flow of energy into the magnetosphere and ultimately predict storm intensity, one must determine how this global \( L \) varies as functions of both solar wind and magnetospheric conditions. Because there is no way to measure this width, \( L \), with individual or small clusters of spacecraft, the value for this fundamental physical parameter remains poorly determined. An important aspect of \( L \) is that it consists of 2 components. If, e. g., bursts of reconnection resulting in flux transfer events (FTEs) dominate reconnection, then one not only needs the distribution of FTE scale sizes, but also their spatial and temporal occurrence rates as functions of solar wind conditions, to calculate their significance to the overall interaction. The global \( L \) would then be an integral of these parameters.

Some models for dayside magnetopause reconnection infer that it begins almost simultaneously over a broad range of local times. Other models predict that reconnection starts in a localized area and then spreads - similar to the visually striking images of ribbon reconnection at the sun. Yet other models suggest a region reconnects, then stops, rather than spreading. Knowledge of the nature of this spreading, in particular its direction and speed or rate is essential to quantify energy input into the magnetosphere. In addition, the processes taking place within the bow shock and magnetosheath, such as magnetosheath jets and mesoscale mirror mode structures, also affect the boundary conditions for reconnection onset.

We also do not know the relative contribution of global separator reconnection versus more localized or transient flux transfer events (FTEs) to the dayside reconnection rate. The problem is analogous to the question of how flow bursts on the nightside contribute to global substorm expansion (Objective 2a). BBFs and FTEs are basic, mesoscale features of magnetic reconnection, and both contribute to the global circulation of mass, momentum and energy in currently unquantified amounts.
Objective 1b. Determine the instantaneous temporal and spatial (particularly longitudinal) extent of energy transfer phenomena

While reconnection is the predominant mechanism governing the entry of solar wind energy into the magnetosphere, it is not the only one. Variations in the solar wind dynamic pressure, whether intrinsic or generated by kinetic processes within the foreshock, readily transfer solar wind momentum and energy into the magnetosphere. Intrinsic instabilities on the magnetopause, such as the Kelvin-Helmholtz instability, also transfer momentum and energy, and even mass, when the instability reaches a non-linear stage. Wave-particle induced diffusion also transfers energy to the magnetosphere.

A variety of kinetic structures generated in the foreshock and magnetosheath such as Hot Flow Anomalies (HFAs) and foreshock bubbles have been proposed to drive the magnetosphere. The few multipoint observations and hybrid simulation results that we have of HFAs indicate they can be large (several RE), have significant impacts on the magnetosphere, and possibly occur several times per day or even more frequently. The figure below shows results from a hybrid simulation of one such HFA, triggered by the IMF rotation indicated by the white arrow. Note the very strong and dynamic impact it has on the magnetosphere. HFAs can trigger reconnection and produce large amplitude boundary waves, but their global impact is unknown and closely linked to their meso-scale spatial structure and temporal evolution.

Boundary waves can also be a major driver of energy and mass transfer into the magnetosphere. An important mechanism is the Kelvin-Helmholtz instability (KHI) which operates frequently and results in meso-scale structures. Recent statistical studies employing single or closely-spaced multiple spacecraft suggest that non-linear Kelvin-Helmholtz waves are far more ubiquitous than originally thought. If so, they may play a more significant role in mass, energy, and momentum transfer. Recent multi-spacecraft studies together with numerical simulations have shown that significant plasma heating occurs via ion-scale plasma waves that are driven by unstable velocity distribution functions driven by the meso-scale Kelvin-Helmholtz waves – an example of micro-meso coupling.

With limited in situ measurements, we cannot determine when or if any of these mechanisms predominate, a major gap in our knowledge of solar wind-magnetopause coupling.
Objective 1c. Compare the total energy input as a function of solar wind conditions and internal conditions and determine the dominant mechanism for specific conditions.

Whether boundary conditions (i.e., the incoming solar wind) or local reconnection physics control solar wind coupling at the dayside magnetopause is a controversial topic with origins in the longstanding Axford Conjecture. It is often simplified to “global” vs. “local” control. Higher densities may throttle reconnection because they reduce Alfven speeds and consequently the inflow velocities into reconnection regions. A blob of dense magnetospheric plasma should therefore reduce reconnection locally. The question then becomes: Does this local reduction in reconnection lead to a decrease in the total energy input from the solar wind? Or does the shocked solar wind in the magnetosheath simply reallocate the inflowing energy by making reconnection more efficient in adjacent areas? This problem starts at the magnetopause but quickly spills into the potential role (or lack there-of) of magnetospheric plasmas in modulating solar wind-magnetosphere coupling or the fueling of storms.

Science Goal 2: Storage and release

The magnetotail, and in particular the near-Earth transition region, is a critical volume of geospace for energy storage and releases, where global circulation of magnetic fields and plasmas is regulated in response to changing solar wind conditions. In it, impulsive, localized flow bursts launch and dissipate, powerful electrical currents form and evolve abruptly, and magnetic energy is explosively converted to particle energy. *The scale, dynamism, and evolution of the three-dimensional magnetotail have evaded our efforts to observe and understand it using individual spacecraft or small constellations. Fundamental questions concerning the dynamic response of the magnetotail and its interaction with the inner magnetosphere and ITM system remain unanswerable with the current observatories.*

Objective 2a. Determine the spatial scales and temporal evolution of mass and energy transport

Impulsive, short-lived plasma flows, termed Bursty Bulk Flows (BBFs) are the elemental unit of nightside plasma transport. In the mid 90’s, the azimuthal size scale of BBFs was inferred to be about 1-3 RE. There have been very few studies that have been able to observe and estimate the azimuthal scale size of BBFs. One such example is shown below left, indicating a narrow flow burst with primarily radial geometry, inferred from a chance conjunction between ISEE-2, AMPTE/IRM, and GOES. Compare that image, based on limited in situ observations, to recent global MHD simulations to the right, and it is clear that our ability to measure the spatial extent and temporal evolution of in situ plasma flows - the plasma flows that are primarily responsible for mass and energy transport from the nightside into the inner magnetosphere and to the dayside - is insufficient. Specifically, the cross-tail structure of the dynamic plasma sheet flows and, therefore, their cumulative effect on the particle and electromagnetic energy transport to the inner magnetosphere remains a major observational challenge.
Just as BBFs are the elemental unit of nightside plasma transport, substorms represent the default mode of transient, impulsive, magnetospheric convection driven by solar wind dynamical coupling. Substorms are composed of some number of BBFs, with each BBF assumed to be the result of transient, localized reconnection in the plasmasheet. THEMIS was designed to answer a narrowly tailored substorm onset question, which at the time was simplified to a dichotomy: substorms either begin with reconnection in the midtail plasmasheet, or substorms begin in the near-Earth transition region via some unknown plasma instability and expand outward. One outgrowth of THEMIS-era substorm studies, greatly enhanced by coordinated ground auroral observations, is a third option - a triggered inside-out scenario, where plasma from the distant tail impinges on the inner magnetosphere, generates an instability that then propagates tailward. The currently limited set of in situ observations have been unable to resolve whether this scenario is, in fact, occurring.

A related prediction for substorm onset, seen in numerical simulations but also suggested by both in situ and remote observations, is a $B_z$ 'hump', wherein $B_z$ increases as a function of radial distance, somewhere in the near-Earth transition region before substorm onset. A $B_z$ hump would represent an area of enhanced instability due to the reversed gradient and could go a long way towards answering questions about how the tail goes unstable. Only one fortuitous alignment of THEMIS probes has reported in situ observations of such magnetic irregularities in the tail; while suggestive it did not yield a definitive answer. Probing the magnetic structure of the magnetotail at low-Earth orbit has also suggested the existence of $B_z$ humps. Together with many simulations, these observations provide smoking-gun evidence that we may be missing a fundamental mechanism of energy release in the tail, which requires formation of inverted magnetic field (and thus flux-tube entropy) gradients. Existing observations are incapable of directly and robustly measuring if these $B_z$ humps occur.

At this point, despite decades of research, there is no consensus on either the initial location of energy release during substorm onset, the mechanisms that cause that release, or the sequence of evolution of substorms. The hindrance has been a lack of multipoint measurements in both
along- and cross-tail directions, at mesoscales, where one could measure the evolution of plasma instabilities and high-speed flow. A constellation of spacecraft with mesoscale resolution is required to finally resolve this fundamental challenge in magnetospheric physics.

In addition to substorms, the magnetosphere has several different ‘modes’ of magnetospheric convection, that appear to depend on the level of solar wind driving and preconditioning of the magnetosphere. Steady magnetospheric convection (SMC) is inferred primarily by ground measurements to be relatively constant return convection, in contrast to the punctuated flows during substorms, but again there are limited in situ measurements to validate this. The existence of reversed magnetic gradients was originally predicted theoretically for SMC as a way for the magnetosphere to resolve the so-called pressure balance crisis. Thus, measuring the mesoscale structure of the magnetic field is fundamentally important for understanding not only steady convection events but also the transition to more active periods and substorms. Geomagnetic storms represent a third type of response mode, and the role of BBFs in energizing the inner magnetosphere is the subject of Objective 2c.

Objective 2b. Reveal the coupling of the MI system at the transition region

The BBFs carrying an enhanced $B_z$ component brake in the tail-dipole transition region and their velocity and the associated electric field vanish. However, the pressure enhancement ahead of a BBF and the plasma vortical motion around them produce a system of Region-1 and Region-2 field-aligned currents (FAC) that is often referred to as wedgements. Closed through the ionospheric currents, the wedgements support a mesoscale dipolarization. Several mesoscale wedgelet are thought to be responsible for formation of a larger scale FAC system known as the substorm current wedge (SCW) that may be a few hours of MLT wide and last hundreds of minutes. That is, these individual wedgelets may integrate to the larger SCW that has been discussed for decades. However, this scenario is highly debatable. The physical connection between transient phenomena, such as BBFs, and larger spatio-temporal scale phenomena, such as SCW, is yet to be established. Just as with FTEs on the dayside, there is a question about how impulsive mesoscale structures integrate to produce a macroscale response. Additionally, we still do not know the magnetospheric drivers of a major mesoscale ionospheric structure, auroral arcs. Even the simplest arc, the growth phase arc that extends for several hours of local time and lasts for many 10s of minutes, remains unexplained. While several theories exist to explain the growth phase arc, the current observational platforms have been unable to provide the needed multipoint measurements. Addressing the open questions of ITM-magnetosphere coupling, and auroral arcs in particular, would benefit from coordinated ground-space observations.

Objective 2c. Determine the source and energization mechanisms of particles injected into the inner magnetosphere.

The plasmasheet is also a region of plasma heating and acceleration, and is known to be a “seed” source of particles for the radiation belts and the ring current. There is great uncertainty concerning the true spatial, temporal, and energy distribution of the 20–500 keV “seed electrons” in the plasmasheet that are further energized via transport into stronger magnetic field regions.
Transport of seed electrons occurs through a combination of processes such as earthward convection, radial diffusion and local acceleration by substorm injections during dipolarization events. As indicated at the figure to the left, which is a simulation of mesoscale flows and the interaction and energization of test particles with these mesoscale structures, particle energization and transport is predicted to be far more complicated than the monolithic particle injection models developed previously. In a similar way, the interaction of plasma sheet ions with the mesoscale flows and electromagnetic field structures significantly deviates from the classical picture of ion convection and drifts in a smooth background field. Complex particle dynamics develop in these interactions, including ion trapping, reflection and scattering, dramatically changing the properties of the particle distribution injected into the inner magnetosphere to create the ring current. A major science objective will be to sort out the relative importance of these various processes in determining the seed populations injected into the inner magnetosphere from the plasma sheet. This is an essential element in developing radiation belt and ring current models to predictive capability.

Mission architecture & concept

The MagCon science traceability matrix (STM) is shown below. Measurement and mission requirements flow from the science objectives and lead to a constellation of in situ spacecraft with particles and magnetic field instrumentation.
Each spacecraft is a small spinner, with body-mounted solar arrays, with the spin-axis roughly perpendicular to the ecliptic, similar to other spacecraft that have explored the magnetosphere such as ISEE-1/2, THEMIS, Geotail, and MMS. The nominal spacecraft design is shown below.

Since the spacecraft are spinning, communication relies on an omnidirectional “garden weasel” antenna design, similar to MMS, which focuses the transmission beam to an azimuthal wedge in a 360° circle. Current design uses hydrazine thrusters with ~450 m/s ΔV, sufficient for all orbit maintenance maneuvers and deorbit. We utilize high-altitude GPS, a next generation Navigator currently on MMS, to enable precise orbit determination even at apogee. Current CBE is a dry mass of 63.62 kg, instrument mass of 7 kg, and 19 kg of hydrazine, for a total wet mass of 88 kg. Observatory uses 40 W of power CBE, and generates 43.15 W EOL.

The science objectives are met with a constellation of spacecraft that collect data in the region of interest covering ~5 RE to ~18 RE, with azimuthal separation at apogee of <~1 RE. The azimuthal separation size scale corresponds to the expected minimum size of flow bursts, and the constellation of different orbits allows for substantial coverage azimuthally (along each orbit) and radially (between orbits and during up and downlegs). Orbits are highly elliptical, coming near-Earth to enable high data rate transmission to ground stations. As shown in the figure, the orbits have...
staggered perigees, with the highest apogee orbits having the lower perigees. This staggered perigee forces the different orbit petals to precess at the same rate, therefore maintaining the same alignment. Without such staggering, the orbits would quickly rotate relative to each other and the constellation formation would be lost.

12 spacecraft are stacked together on a single ESPA grande, then 3 ESPAs are stacked together for a full stack of 36 spacecraft. We utilize the launch vehicle to place the deployers into the needed orbits. Preliminary analysis shows that a Vulcan Centaur with 6 solids can carry the entire stack, deploy, and deorbit the upper stage. The deployers are then responsible for timing deployments to establish a string-of-pearls of 12 spacecraft along the orbit. Once deployment is complete, the ESPA uses onboard propulsion to deorbit.

Mission measurements

As indicated in the STM, science objectives are answered with measurements of the in situ electron and proton pitch angle distributions at 3-s resolution, with energies up to several 100 keV to capture energization as particles are transported into the inner magnetosher. Magnetic field is required at 10 Hz. Science objectives are achievable with ‘standard’ ESA, solid state telescope, and fluxgate magnetometer, although there is room for an additional low SWaP particle instrument.

Cost

Cost estimates for the spacecraft (WBS 5.0) are based on MELs and costed by NASA GSFC, and historical estimates for the instruments. Deployers are assumed to be commercial propulsive ESPAs, modified as needed. Wrappers are applied to WBS 1.0 (7.0%), 2.0 (5.0%), 3.0 (4.0%), and 4.0 (7.0%). Mission operations and ground systems are estimated based on current missions and past performance.

Phase A-D mission cost, excluding launch vehicle, is $798.6M (FY21), and $1038.1M (FY21) with 30% reserves. Phase E-F costs are $91M (FY21) and $118.3M (FY21) with 30% reserves. Total A-F costs, without LV, are $889.6M (FY21) and $1156.4M (FY21) with 30% reserves.