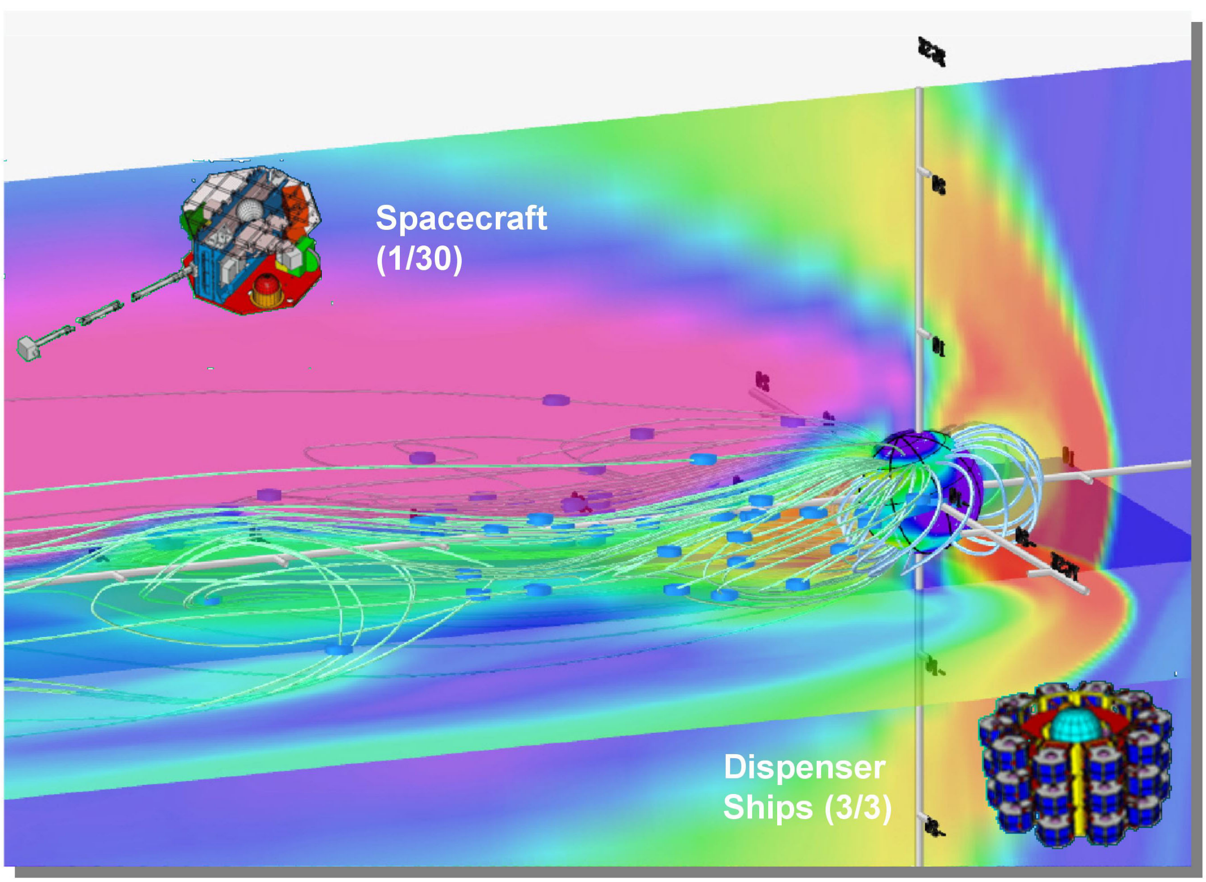
The Magnetospheric Constellation (MC)

Global Dynamics
of the Structured Magnetotail

Updated Synopsis of the
Report of the NASA Science and Technology Definition Team
for the Magnetospheric Constellation Mission

October 2004

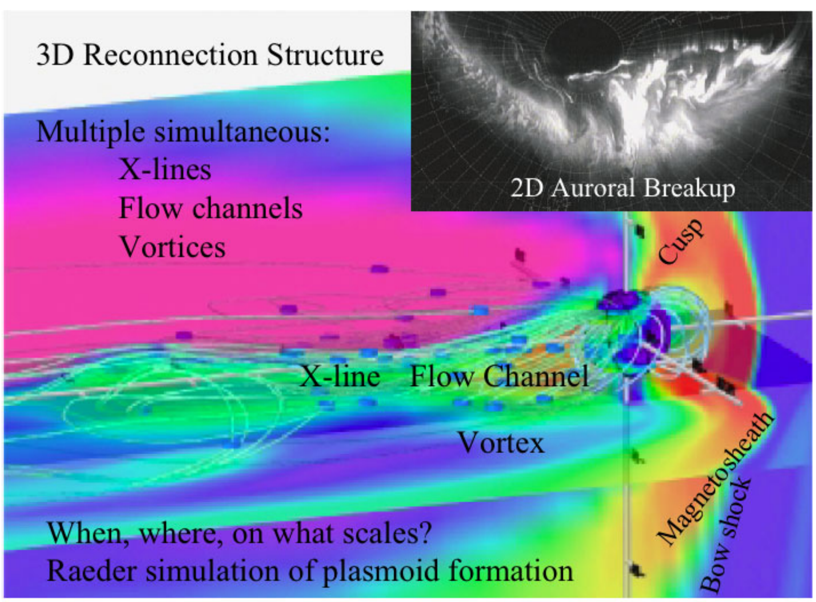


Executive Summary

The Magnetospheric Constellation (MC) mission, with its distributed network of *in situ* observing stations, is the ultimate tool for unraveling the mysteries of magnetospheric storage, processing, and release of solar wind energy. Forty years of studies with individual or widely separated spacecraft have been illuminating but ultimately inconclusive in terms of understanding the fundamental physics. It is as if we had attempted to understand tropospheric dynamics using a single mobile weather station or, perhaps, since there has been an international effort, one in every nation. Given a thoughtful plan for deployment, each mobile station would record many intriguing phenomena and build suggestive statistical data sets, but these could never support a full, predictive understanding of such a richly nonlinear dynamical system.

To create a station network, the MC mission will use three dispenser ships, each comparable in size and complexity to a typical magnetospheric spacecraft. Each will deploy ~10–12 spacecraft of the ST–5 class into nested elliptical orbits with common perigees and apogees ranging from 7–27 R_E altitude, at an inclination that maximizes the time spent in the plasma sheet. The spacecraft will have the typical spacing of ~2 R_E. The science payload will deliver magnetic field, plasma density, temperature and flow, and energetic particle angular distributions, at 10 sec resolution, with low-frequency waves up to 100 Hz.

Visualizing the magnetospheric constellation mission with the help of global simulations from J. Raeder. Inset is auroral imagery from a DMSP spacecraft.



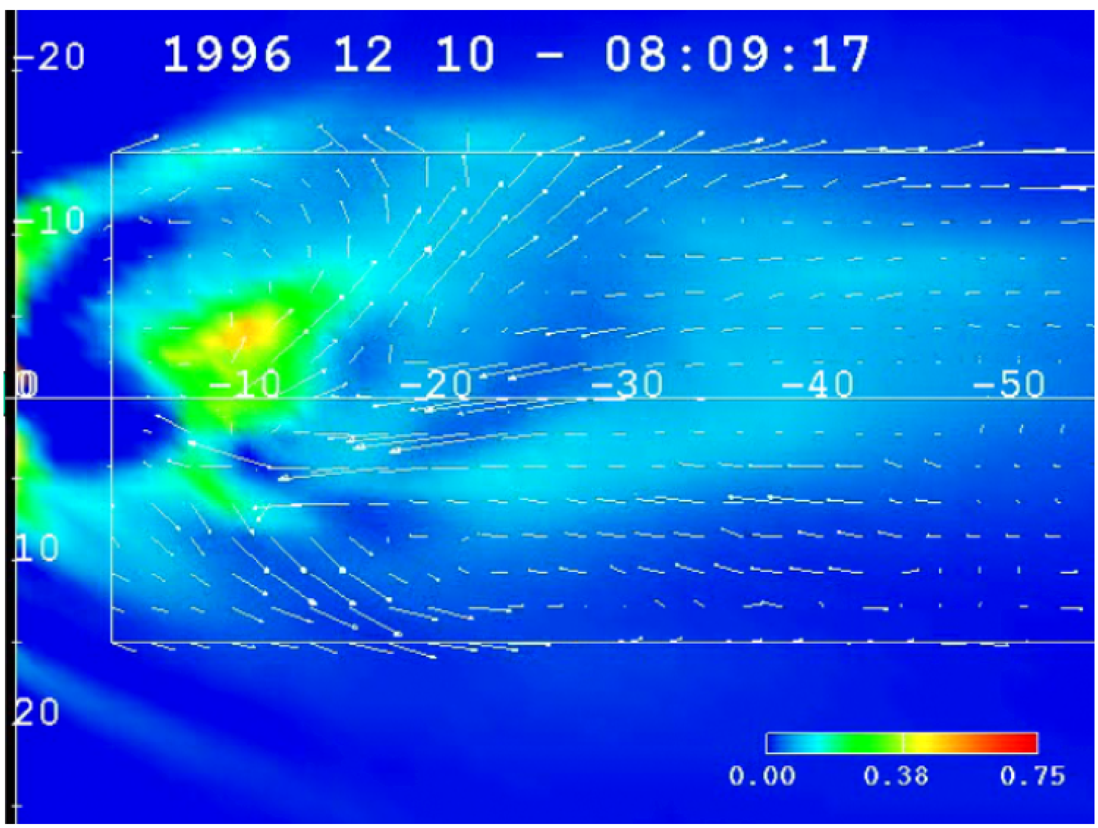
It might be argued that a key breakthrough in surface weather studies was the development of global imaging systems, operating from space. Recently, imaging missions have demonstrated the power of remote sensing of geospace using a spectrum of electromagnetic wavelengths and fast neutral atoms. Moreover, the effectiveness of a close formation of 3–4 spacecraft has been clearly demonstrated for studying the nature of boundary layers and other narrow structures in geospace. With a combination of imaging for large scales and spacecraft clusters for the boundary layers, why do we need a multipoint *in situ* station network in geospace?

The answer is that, important as boundary layers and the inner magnetosphere are in geospace, the domain of solar wind interaction is large, laced with electromagnetic and particle flow fields that cannot be imaged, and it is known to contain important dynamics at scales inaccessible to clusters of spacecraft, such as extended reconnection X lines, flow channels, and flow vortices. In the near term, steps can be taken and considerable progress can be made using well-conceived, one-dimensional arrays of spacecraft, deployed along a radius or an arc of longitude. However, physical understanding of system dynamics across all scales will ultimately require a two-dimensional station network of spacecraft encompassing the principal regions of interaction between the solar wind and ionospheric plasmas. This is the function of the Magnetospheric Constellation mission, which, owing to the New Millennium ST–5 trailblazer and other studies summarized herein, is ready to be implemented today.

Introduction

THIS IS A SHORT, UPDATED SYNOPSIS OF the Science and Technology Definition Team (STDT) report, *The Magnetospheric Constellation Mission: Dynamic Response and Coupling Observatory (DRACO)*. The original report (and other relevant documents) is available at *http://stp.gsfc.nasa.gov/missions/ mc/documents/*. Our purpose here is, first, to clarify and refine the science focus of the Magnetospheric Constellation (MC) mission and to establish science priorities by which the anticipated productivity of the mission can be evaluated, in light of developments since the 2001 report was released. We also report on several refinements of the mission definition that have come out of a series of four engineering studies performed by the GSFC Integrated Mission Design Center (IMDC). These studies, based on the ST–5 spacecraft bus, show that there no longer are technology obstacles to overcome for this mission.

The magnetotail is a critical volume of the geospace environment wherein 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 fundamental plasma process known as magnetic reconnection is thought to occur during substorms, an important building block of "space weather." These are recurrent impulsive energy releases that become more frequent during magnetospheric storms. The scale, dynamism, and turbulent evolution of the magnetotail have humbled our efforts to observe and understand it using individual spacecraft. The magnetotail magnetic fields and plasmas do possess an underlying, slowly varying coherent structure, but strongly turbulent flows and

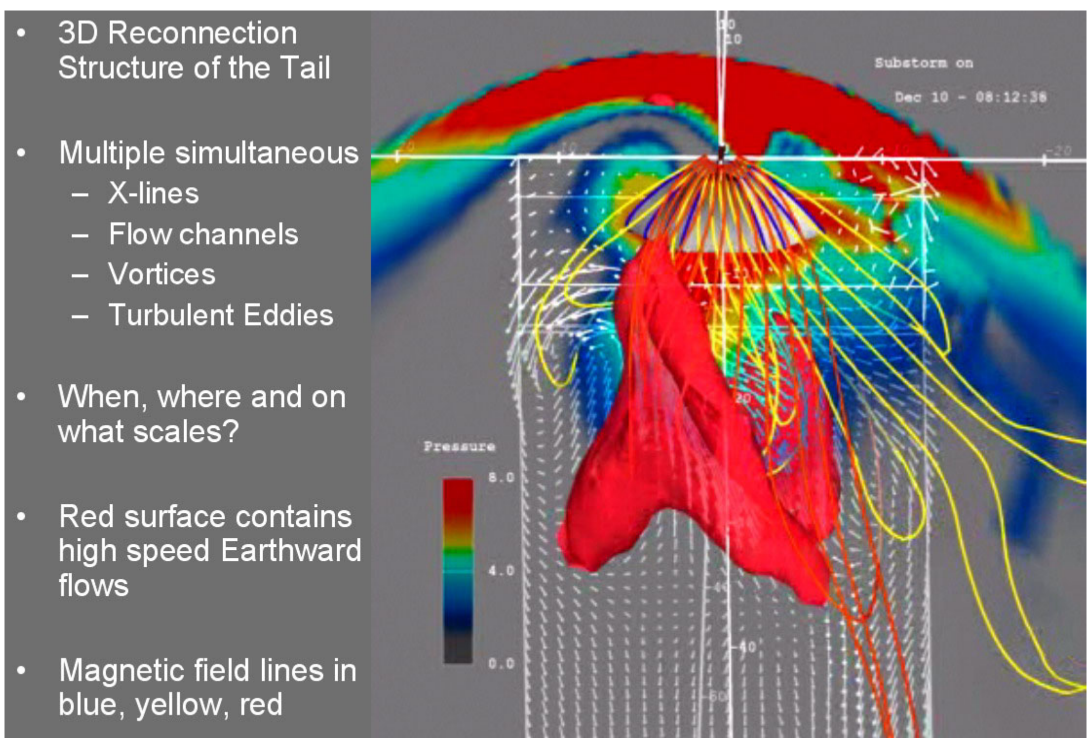


The flow field and plasma current generated by the Lyon–Fedder–Mobarry MHD simulation of the magnetotail, during a channel-like flow burst.

fields usually are large compared to the mean field or flow. Thus, globally coherent pictures of the system dynamics become lost in the “noise” of individual measurements. Despite more than 30 years of research with ever more sophisticated instrumentation on ever larger and more complex spacecraft, fundamental questions concerning the dynamic response of the magnetotail remain unanswerable. Accordingly, scientific progress has slowed. Intelligent, reasonable scientists cannot reach consensus on these issues, not for lack of models and theories, but because of a lack of relevant measurements. Neither current single spacecraft, nor tight clusters of spacecraft, can fully resolve these fundamental controversies.

To provide the first-ever two-dimensional, time-evolving vector field and streamline images of this important region, MC will deploy a “constellation” of small spacecraft from a single launcher. With resources of 20–25 kg and 15–18 W apiece, 30+ MC spacecraft will be deployed in elliptical, equatorial orbits with common perigee altitudes of 1 R_E and apogee altitudes distributed from 7 to 27 R_E, yielding mean interspacecraft separation of ~2 R_E. Enabling technologies for MC have been developed for the ST–5 Nanosatellite Constellation Trailblazer mission of the New Millennium Program. MC is now ready for definition and development.

Magnetospheric Constellation is the logical outgrowth of a sequence of Explorer and STP missions, designed to explore plasma transport and energy conversion processes over spatial sizes ranging from the distance to the Sun to the size of low-energy particle gyro-orbits. The Magnetospheric Multiscale (MMS) mission will focus on the smallest scale, microphysical processes occurring within and near magnetospheric boundary layers: magnetic reconnection, charged particle acceleration, and eddy turbulence. It will serve as the plasma physical “micro-



Visualizing magnetotail dynamics with the help of the Lyon–Fedder–Mobarry global simulation, showing magnetic field lines, plasma flow field, and plasma pressure. The highest speed Earthward flows are enclosed by the red surface.

scope," investigating scales too small to be resolved by global circulation models. The THEMIS mission targets an alignment of five spacecraft along a radius extending into the magnetotail, for a one-dimensional view of the magnetotail, a substantial advancement over the study of complex phenomena using individual spacecraft. MC will establish a 2-D array of spacecraft both along ***and*** across the magnetotail, designed to serve as a "meso/macroscope" that can truly "image" and make dynamic movies of magnetotail vector fields. Ultimately, it will yield a new understanding on which we shall build a predictive science of next-generation magnetospheric meteorology and forecast models, adding to our collective body of knowledge relating to complex nonlinear dynamical systems.

Science Objectives

The overarching objective of the MC mission is to determine how the magnetosphere stores, processes, and releases energy derived from the solar wind interaction, accelerating particles that supply the radiation belts. This is still the central mystery of magnetospheric physics. In the following subsections, we expand this objective in three areas.

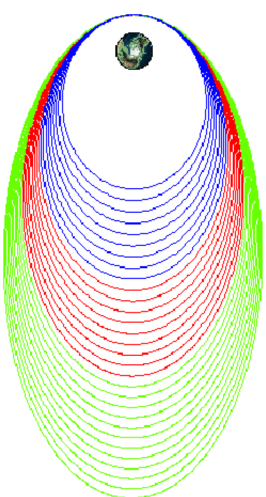
1. Magnetotail Dynamics

Key Question (1)
How does the magnetotail behave?

Recently, it has been shown that bright nightside auroral UV emission regions evolve in every measurable relevant manner exactly like avalanches in numerical models of self-organized criticality (SOC). Such models describe the transport of a conserved quantity from a region where it is loaded into the system to a region, usually a boundary, where it is unloaded. This transport is enabled only at spatial locations where a localized instability is excited. If the model dynamics are in the neighborhood of "criticality," then intermittent, bursty cascades of instability, usually called avalanches, result. These avalanches have the defining property that no characteristic spatial, temporal, or energy scales can be found in their distributions over the entire range of scales defined, at the high end, by the global scales of the system and, at the low end, by the scale sizes associated with the localized instability mechanism; the avalanches are "scale free." The question seems unavoidable: Why should auroral UV emission regions behave in this manner?

The relationship of nightside auroral UV emissions to fast flows generated by reconnection in the plasma sheet is now well established. This relationship has been known for decades in the case of global substorm events and auroral expansions. More recently, however, it has been shown that even isolated localized reconnection in the plasma sheet leads inevitably to small auroral bright spots, even during otherwise geomagnetically quiet periods. Bursty bulk flows (BBFs) and pseudo-breakups are similarly related to auroral emissions at intermediate scales. Reconnection events in the plasma sheet occur over large ranges of spatial and temporal scales and produce nightside auroral emission events over similarly broad ranges of scales.

The magnetotail loading and unloading cycle, of magnetic flux or energy, plays a central role in the substorm . The scale-free distributions of bright nightside auroral emission properties, combined with the relationship of reconnection in the plasma sheet to auroral emissions, shows that the unloading of magnetic flux or energy in the tail is carried by



The initial nested orbits of the MC mission, with coloring to indicate the inner, central, and outer family of orbits.

avalanches of localized reconnection events, the temporal, spatial, and magnitude scales of which are distributed uniformly over broad ranges. Substorms, pseudo-breakups, and BBFs are members of a continuous distribution of such manifestations of instability in the magnetotail.

Key Question (2)
How are particles accelerated to form the radiation belts?

It is the nature of scale-free avalanching systems that all scales are strongly coupled nonlinearly; they all play an important role in the unloading process. Substorm activity in the magnetotail involves all spatial scales ranging from those associated with localized fast flows, ~1–2 R_E and possibly smaller, up to the largest scales that can be contained in the tail, as well as all temporal scales ranging from a few tens of seconds as determined from the auroral emission studies, up to several hours, the typical substorm duration. To understand the substorm mechanism in the magnetotail, the plasma sheet must be observed over all of these spatial scales simultaneously and continuously. Only a constellation of spacecraft that is distributed over the plasma sheet can accomplish this.

MC observations will be used to (1) determine the spatial distributions of reconnection and related fast flows in the magnetotail, (2) track the evolution of these distributions over the substorm cycle and in response to changing solar wind conditions, (3) determine the requirements for the onset of the global avalanche events called substorms, (4) reveal the plasma physical principles that lead to a scale-free avalanching magnetotail, and more. Thus, the fundamental nature of activity in the magnetotail will be revealed by the distributed constellation of spacecraft that the MC mission will provide.

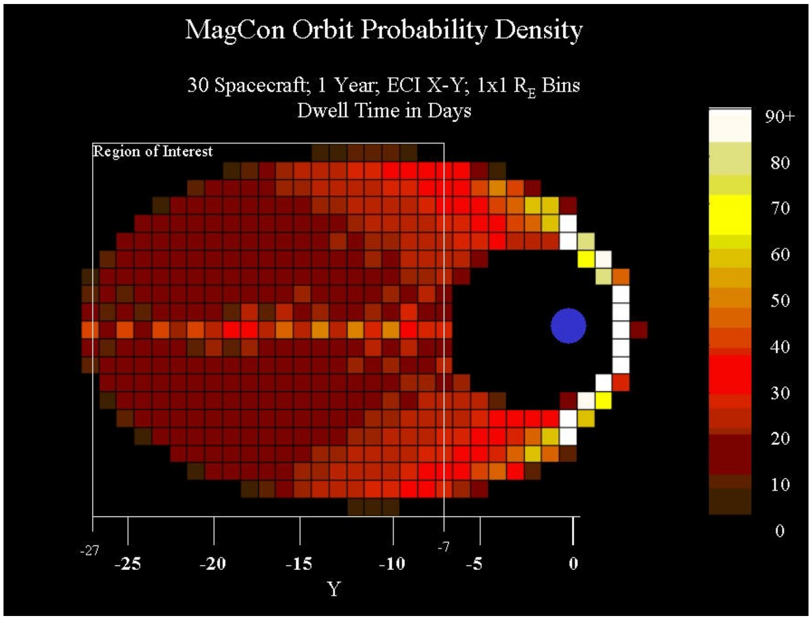
Artist's concept of the spacecraft and dispenser ships stacked in the vehicle shroud.

2. Particle Acceleration

The plasma sheet is known to be a source of particles from which are generated the variable components of the radiation belts. A framework for radiation belt dynamics has been established on the basis of missions like CRRES and Polar. However, there is always great uncertainty concerning the true spatial, temporal, and energy distribution of the "seed electrons," having energies of 20–500 keV, 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. ULF waves are active in electron acceleration through mechanisms as diverse as drift resonance, magnetic pumping, and transit-time acceleration. VLF waves are involved in electron acceleration as well as in precipitation and loss. The objective of the MC mission 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 models to predictive capability.

A constellation array of spacecraft should provide simultaneous observations of the plasma sheet and of the outer radiation belt/ring current region. These observations will permit us to (1) compare the electron distribution as a function of radial distance and local time and, using models, to distinguish between diffusive and convective ef-



Sampling probability density plot for the MC mission with 30 spacecraft in the orbits indicated.

fects, (2) determine the acceleration response to interplanetary conditions and structures, (3) determine the flux response to activity measures, including storm fields, wave power, and auroral activity, (4) measure energetic particle precipitation and loss rates throughout these regions, and (5) identify magnetic field or plasma boundaries in the regions, thereby determining the degree and extent of magnetospheric coherence.

Key Question (3)
How does the magnetopause respond to the solar wind?

3. Dayside Magnetopause Science

The MC mission will provide observations critical to determining the dominant mode of solar wind–magnetosphere interaction at the dayside magnetopause. A wide variety of models has been proposed to account for that interaction. Some models invoke steady processes such as reconnection along an extended neutral line or widespread diffusion induced by wave–particle interactions. Other models invoke transient local processes such as the Kelvin–Helmholtz instability or bursty reconnection driven by intrinsic magnetopause instabilities. Still other models invoke bursty merging or boundary waves triggered by the highly variable solar wind input (or the significant perturbations introduced into the solar wind by processes occurring within the foreshock).

The signatures of each of the proposed mechanisms are well known. Reconnection produces high-speed plasma flows on interconnected magnetosheath–magnetosphere magnetic field lines, whereas diffusion produces a low-latitude boundary layer on closed magnetic field lines, the dimensions of which grow with downstream distance. Bursty reconnection produces flux transfer events, or FTEs—bundles of interconnected magnetic field lines that bulge outward into both the magnetosheath and magnetosphere. The Kelvin–Helmholtz instability produces anti-Sunward-moving waves on the inner and outer edges of the low-latitude boundary layer. Pressure pulses in the solar wind drive waves that propagate dawnward or duskward across local noon in accordance with the spiral/orthospiral IMF orientation.

The significance of each proposed mechanism depends on the amount of mass, momentum, and energy it transfers to the magnetosphere as a function of solar wind conditions. These parameters can, in turn, be estimated from the occurrence patterns and spatial dimensions of the phenomena generated by each mechanism. To date, the lack of widespread observations has precluded accurate estimates. However, the Constellation array of spacecraft will provide precisely the observations needed to make the estimates: simultaneous magnetopause, magnetosheath, foreshock, and solar wind observations over a wide range of local times.

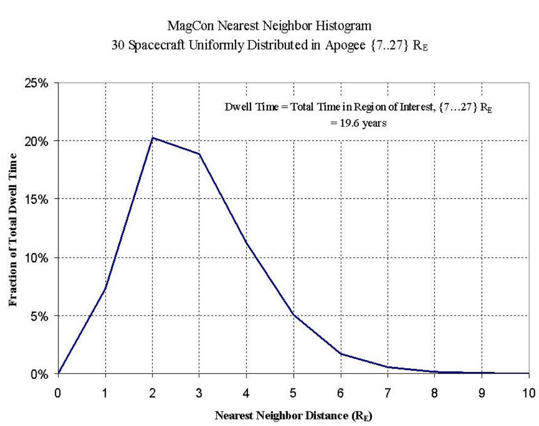
Constellation observations will be used to (1) compare the precisely determined characteristics expected for each of the proposed interaction mechanisms with observations, (2) determine occurrence patterns as a function of solar wind conditions, (3) determine the longitudinal extent of individual phenomena, (4) track their longitudinal motion, and (5) determine amplitudes in the direction normal to the magnetopause. In conjunction, these observations will provide a decisive answer to some of the most long-standing and controversial questions in magnetospheric physics.

Mission Top-Level Requirements

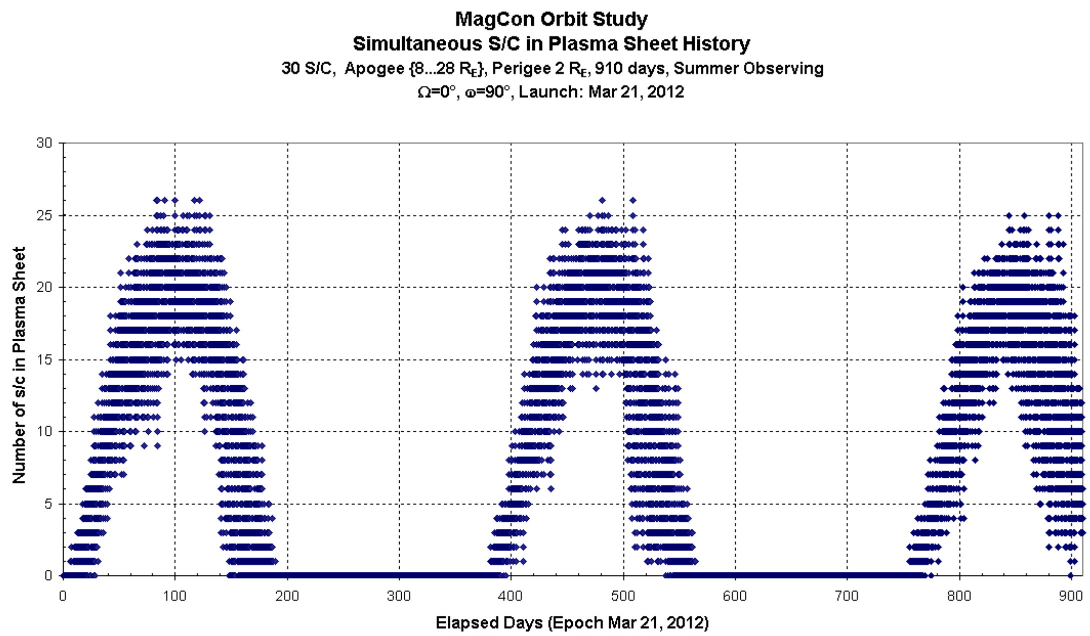
Requirement	Parameter	Value
Provide 2-D spacecraft array spanning the region from geosynchronous orbit to the flow reversal region in the midtail.	Max. apogee Min. apogee Perigee	27 R_E 7 R_E Min. Cost
Provide spatial resolution of 2-3 R_E.	No. of spacecraft	30
Provide time resolution adequate to resolve convection flow bursts.	Measurement cadence	10 sec.
Provide measurements of MHD quantities: magnetic field and waves, plasma flow, and pressure.	See payload requirements	

Mission Design

To achieve its science objectives, MC must have a mission lifetime of sufficient duration to observe magnetotail behavior during a variety of solar wind conditions and at least a sampling of typical solar wind disturbances, including co-rotating interaction regions and Coronal Mass Ejections (CMEs). The entire constellation should be put into orbit with apogees in the local time range around local dawn. Initial activation would then be completed well in advance of the rotation of the tail across the Constellation orbit pattern as Earth orbits the Sun. This would produce, early in the mission, a pioneering but ancillary study of the dawn flank of the magnetosphere and its interaction with the magnetosheath. A main mission phase would follow as the Constellation passes through the center of the magnetotail over a period of roughly 4 months. This, in turn, would be followed by a study of the dusk flank and boundary layer interactions. All of these would occur during the first 6 months of operation and would achieve the minimum success criteria for the mission. Continued operations over a subsequent year would produce unprecedented studies of the dayside magnetopause, magnetosheath, bow shock, and foreshock regions. With the completion of this first dayside sci-



The probability distribution of nearest neighbor spacings between the spacecraft.



Mission evolution of the number of spacecraft within a model plasma sheet during the first three mission passes through the midnight plasma sheet.

ence phase, MC would be in position for a second pass through the tail beginning 1 year after launch.

MC must establish its spacecraft array in the magnetotail region from about 7 R_E to 27 R_E in the nightside along the Sun–Earth line, and across the magnetotail east and west of the Sun–Earth line by ~10 R_E. This is based on the importance of phenomena within the region from geosynchronous orbit to beyond the fast flow reversal associated with substorm activity, near 25 R_E. Eccentric orbits with perigees near 1 R_E provide an optimal trade between orbit stability and economical transmission of commands and data. A set of orbits with apogees ranging from 7 to 27 R_E will provide all the coverage that is needed. Careful study of the constellation orbit options has been performed to determine that 30 satellites will give adequate spatial coverage to achieve approximately 2 R_E mean spacing of spacecraft with random orbital phases, when the constellation is placed at an inclination of 15°.

An innovative deployment plan has been developed that uses modular deployer ships to place groups of 10–12 satellites into separate orbital groups. The deployer ships are essentially propulsion unit shells that are powered and controlled by the MC satellites, which contain all avionics, solar cell arrays, and software to accomplish this. Each deployment unit, with its payload of 10–12 satellites, is comparable in mass and volume to a single MMS spacecraft. Any of the identical satellites is capable of controlling the deployer, providing high redundancy. One satellite on each deployer is designated as the controller and the rest serve as backups.

The use of multiple ships to independently deploy spacecraft to the inner, central, and outer orbits provides a substantial enhancement of the propulsion efficiency of the deployment. It also allows for different parts of the constellation to have different orbital characteristics, providing additional flexibility. For example, by keeping the eccentricities of the three orbit families similar, differential precession of the groups can be reduced.

Science Payload

THE SCIENCE MEASUREMENT OBJECTIVES have not changed from those described in the 2001 MC STDT Report. However, substantial definition of the instrumentation has been accomplished. A magnetometer has been developed, fabricated, and tested for the ST–5 mission, including a lightweight deployable boom. In addition, conceptual designs have been developed for the plasma velocity analyzer and energetic particles detector. Further, a study is underway, under SECID support, that will better define a multisensor controller for all MC instruments. We provide brief descriptions of the instruments envisioned below.

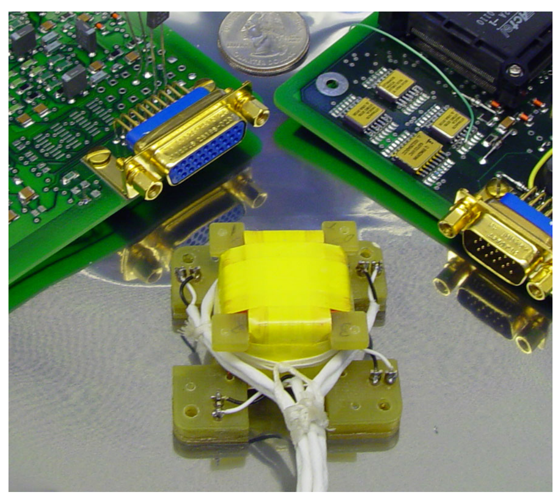
The ST–5 magnetometer (MAG) is a research-grade miniature vector magnetometer provided by UCLA. It covers a range from 0–64000 nT with intrinsic noise <0.1 nT RMS. Digital resolution is better than 1 part in 5000. Resources are 420 gm and 500 mW. The time resolution available for wave spectral studies is 100Hz.

The MC Plasma Velocity Analyzer (PVA) is conceptually a pair of half

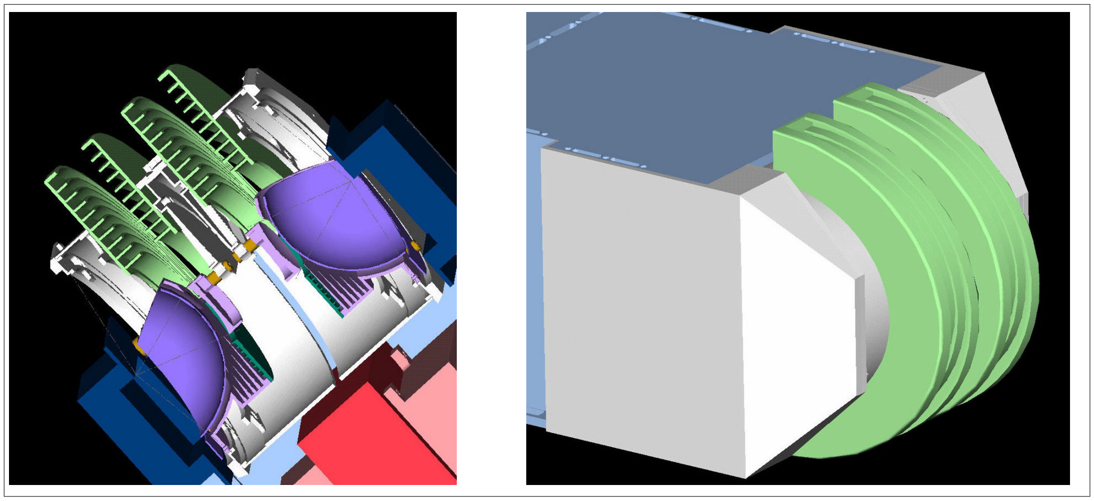
Payload Requirements

Measurement	Range	Resolution	Time Res.	Comments	Mass	Power
3-Axis Magnetic Field*	+/- 300 nT	0.1 nT	1 sec.	Fluxgate technology exists	420 gm	500 mW
Plasma 2-D Temperature	10-20,000 eV	20%	10 sec.	Requires 180 deg field of view	1500 gm	1500 mW
Plasma Flux	10^2-10^8 cm^{-2} s^{-1} sr^{-1} eV/eV	20%	10 sec.	Electrostatic analyzer technology exists		
Plasma 3-D velocity Electron PAD	1-1,000 km/s	20% 20 deg	10 sec.	Mass analysis significant but not absolutely required		
Particle Energy	20-500 keV	20%	10 sec.	Mass analysis significant but not absolutely required	1200 gm	900 mW
Particle Flux	1E0-1E6 cm^{-2} s^{-1} sr^{-1}	20%	10 sec.	Solid-state telescope technology		
Particle Pitch Angle	180 deg	20 deg	10 sec.			

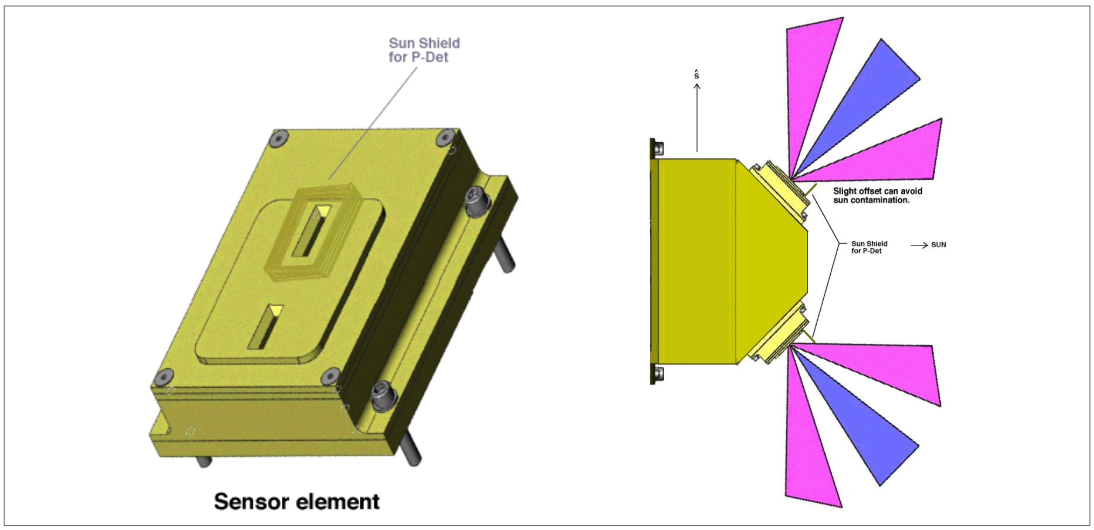
**100% measured.*



The MC magnetometer is based on this ST–5 magnetometer hardware.



The MC plasma velocity analyzer is based on a pair of conventional top hat analyzers with 180° field of view for electrons and ions.



The MC energetic particle analyzer is based on conventional solid-state telescope designs, arranged so as to form a 180° field of view for electrons and ions.

(180° FOV, swept by spacecraft spin) top hat electrostatic analyzers packaged head to head with entrance apertures aligned to view through a common spacecraft opening. In practice, the electron analyzer may be smaller than the ion analyzer, in view of larger typical fluxes. Both analyzers are equipped with automatic aperture control or sensitivity control to enable them to handle high magnetosheath fluxes encountered when the spacecraft are outside the magnetosphere.

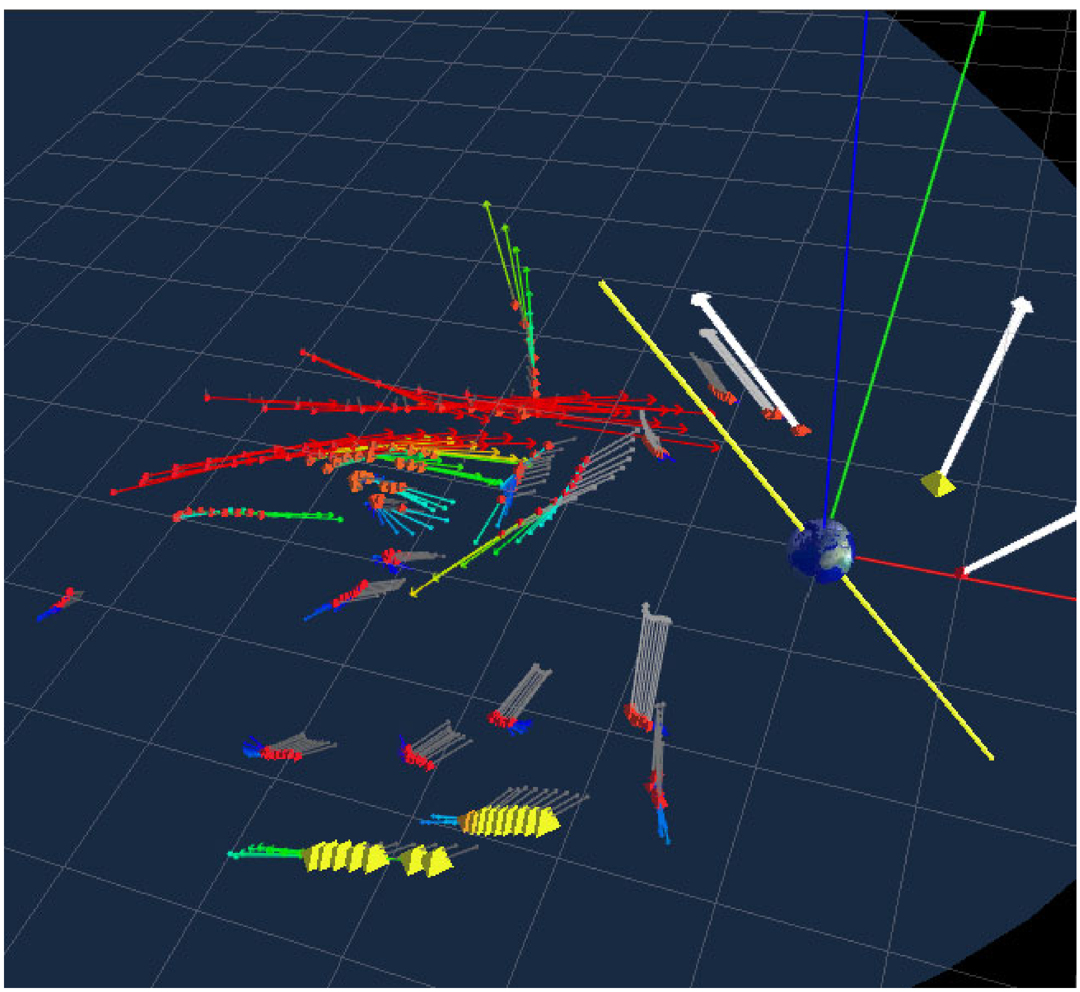
The MC Energetic Particle Analyzer similarly provides a 180° (swept by spacecraft spin) field of view for both electrons and ions, based on a pair of sensor units mounted at 45° to each other. Each identical sensor element contains three electron and ion pixels, providing six broad polar angle channels.

Data Synthesis

The Magnetospheric Constellation mission will provide multipoint *in situ* magnetospheric measurements of substantially greater quantity than any previous mission. Making optimal use of the measurements will require the development and application of new techniques. The implementation of the MC mission will result in a leap, similar in its importance to the one made by atmospheric physicists decades ago. Initially, individual weather observations were gathered into synoptic maps (summarizing a large number of individual observations). Later, the maps came to be further processed using spatial objective analysis and data assimilation. These techniques developed for the atmospheric sciences over the past decades can be borrowed to solve the new analysis challenges of MC.

Assimilation of data can minimize errors in both the data and the model, even when the model suffers from simplifying assumptions, and thus provide an optimal "map" of the physical state of the magnetosphere at any given time. Data assimilation techniques have been successfully used in atmospheric and oceanographic models for some time, but never before in magnetospheric modeling. The primary reason that data assimilation methods have not yet found their way into magnetospheric modeling is the scarcity of magnetospheric *in situ* measurements. The MC mission will change that dramatically by providing, for the first time, a usefully dense grid of *in situ* data describing the state of the entire modeled system.

The power of data assimilation has been demonstrated convincingly by the numerical weather prediction models, which all use assimilation techniques. Employing these techniques in magnetospheric modeling will result in a dramatic breakthrough, since the data assimilation will serve as an ultimate test of the underlying model's quality. Any systematic divergence of a model from the data will provide a clue to some intrinsic deficiency to be correct-



The flow field and magnetic field generated by the Lyon–Fedder–Mobarry MHD simulation, as measured by a virtual Magnetospheric Constellation mission. Gray vectors represent the local magnetic field, while colored vectors represent the plasma flow field with a time history from each spacecraft displaced from the observing point according to the flow measurement. The red trail of vectors clearly delineates the channel-like flow burst during this period.

ed. In addition, not only will the model improve overall, but also new knowledge will be gained about the physical processes, whose incomplete or wrong description had caused the model to fail. In short, the data assimilation forces a continuing reevaluation of our understanding of how the magnetosphere works. This is one of the primary drivers for the MC mission.

Relevance to Sun–Earth Systems Science

The Magnetospheric Constellation mission will establish a fundamentally new capability for the study of connections between the solar wind and Earth's atmosphere and will make possible the first *synoptic* studies of the magnetosphere, with impacts fully comparable to the advent of station networks for the study of tropospheric weather. We can announce here the likely advances and contributions that will be made using truly synoptic magnetospheric data, but it must be admitted that substantial surprises are almost inevitable when so large a leap in capability is developed.

The elusive central goal of magnetospheric physics has been to determine how the magnetosphere stores, processes, and releases energy in the magnetotail, the role of important physical processes therein, and how these processes interact across all scales up through global. Earlier missions with lone or widely spaced spacecraft have proved inconclusive with regard to this objective, just as observations from individual weather stations were inconclusive until a network of stations provided synoptic data.

Synoptic: adj.
1. Of or related to data obtained nearly simultaneously over a large area.
2. Manifesting or characterized by comprehensiveness or breadth of view.

MC will create a synoptic data base of magnetotail observations within which magnetospheric phenomena will be fully depicted rather than debated. Having this, we will move on to debate the physical processes that must be included in our simulations to capture these phenomena and account for them. We will emerge from a long and frustrating hiatus during which the limitation of space missions to single station, or small groups of stations, crippled progress on the understanding of geospace activity.

In addition, MC will be a trailblazing mission for other constellation missions of the future. For example, an inner magnetosphere constellation and a heliospheric constellation are under consideration as part of the most recent Sun–Earth Connections Roadmap. MC and other constellations will be highly complementary to the missions of the Living With a Star Program (LWS), particularly the Radiation Belt Storm Probes and the Heliospheric Sentinels.

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