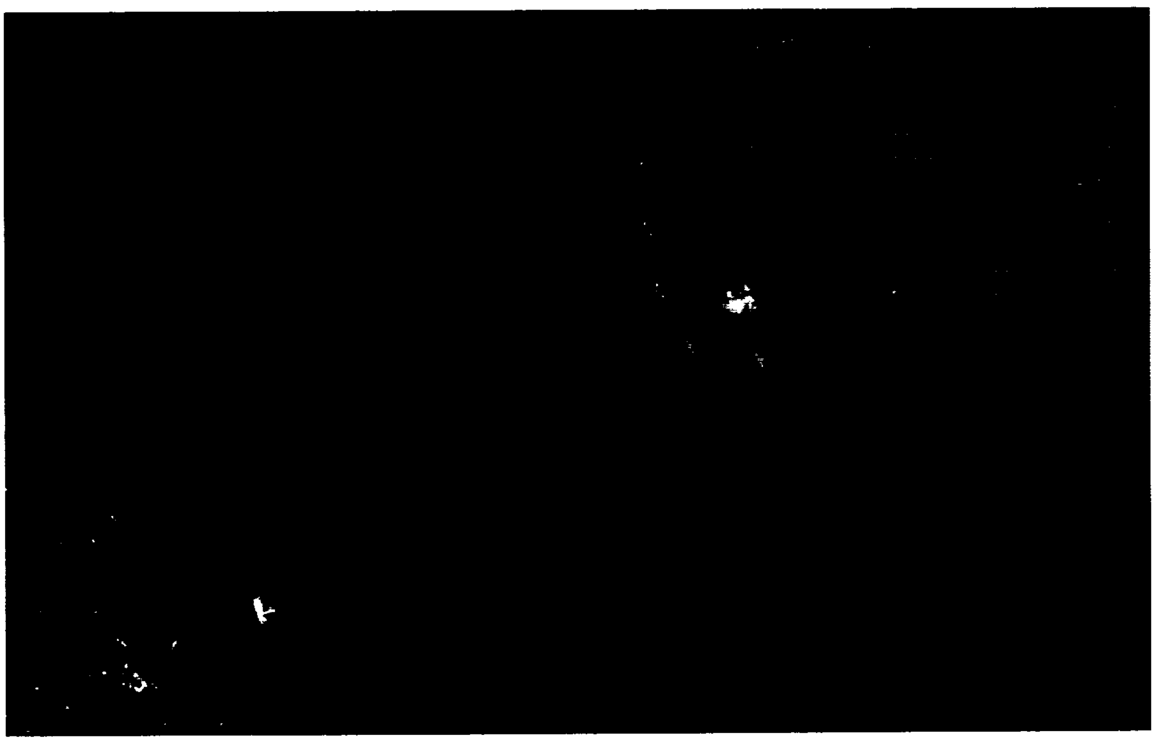
Geospace Multiprobes



Report From The Science Definition Team
December 1997

GEOSPACE MULTIPROBES

REPORT FROM THE SCIENCE DEFINITION TEAM

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Executive Summary

The Earth's upper atmosphere and space environment, termed "geospace," are important from the perspective of fundamental astrophysical processes. They are also becoming increasingly important for their practical effects on space based and globally distributed engineering infrastructures (e.g. the effects on communications, navigation, power distribution, etc.) Many fundamental scientific questions regarding the behaviors of these environments will require new approaches for resolution. One of the new approaches that is necessary, and becoming increasingly viable given technological advances, is the use of multiple diagnostic satellites that are operated in highly controlled and coordinated fashions with respect to each other. Missions utilizing such "multiprobe" approaches can:

1) Separate spatial and temporal variations in the geospace environment.
2) Expose cross-scale coupling processes that are prevalent in the geospace environment.
3) Provide spatial and temporal sampling that are commensurate with theoretical models and data assimilation procedures.

These unique features of the multiprobe approach are the critical factors in moving from a phenomenological characterization of geospace to an understanding of the fundamental processes that control the behavior of geospace.

In order to understand the response of the system to external drivers we must understand how the geospace environment processes the energy and mass flow that are delivered to it and we must understand how the redistribution of energy and mass within the system is accomplished. One must appreciate the fact that the behavior of the geospace system cannot be specified by knowledge of only the driving inputs. Rather, there is a connection between the driving inputs and the existing state of the system that determines its response. The response can be very dynamic and perturbations that originate in relatively small regions can propagate throughout the system on time scales of a few minutes to a few hours. We have made great strides in achieving a phenomenological understanding of the geospace response that has been spurred by previously successful space flight missions and the ongoing ISTP program. The upcoming TIMED mission will yield similar improvements for the upper atmospheric regions. These missions can and will uncover the magnitude of changes that take place when external drivers change and the relationships between changes that take place in widely different regions of geospace. However, there are fundamental gaps in our understanding of the picture. We do not understand how the changes are effected and we do not understand which of a variety of processes might be responsible for the related changes. This gap in our understanding results primarily from the large range of spatial scales that operate in an extremely large volume. The coupling between these scales throughout the volume of geospace must be understood. Such an understanding can only be reached with simultaneous measurements at multiple locations with variable spacing in geospace.

In this report we describe three geospace multiprobe missions that could provide the first giant steps forward. A Magnetospheric Multiscale Mission will examine critical boundaries in the magnetosphere with spatial scales from kilometers to several Earth radii. The low-altitude extent of the geospace environment will be investigated to understand energy dissipation in the upper atmosphere by the Global Electrodynamics Mission. The processes mediating global transport of energy and momentum in the magnetosphere will be investigated by the Magnetospheric Constellation Mission.

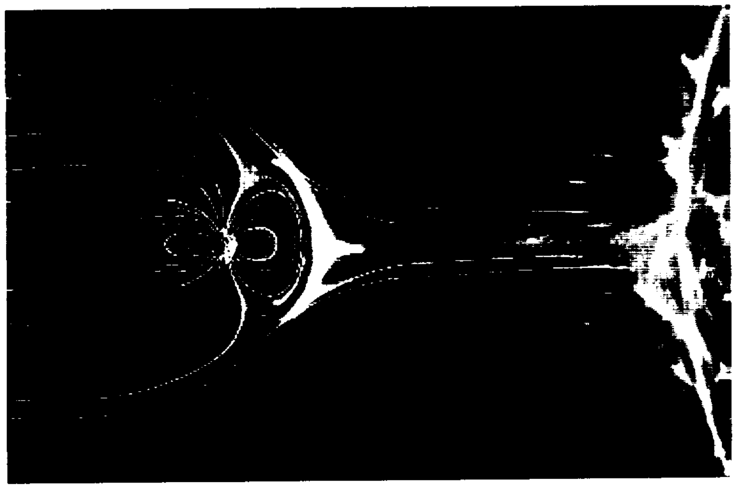
The Magnetospheric Multiscale Mission employs six spacecraft to combine insitu measurements of temporal and spatial features in the magnetosphere with global imaging that delivers a description of the global response of the system. Two spacecraft will provide the imaging capability while four identically instrumented satellites will fly in formation to different locations in the magnetosphere where critical energy and mass transport processes occur. At these locations (in the magnetospheric tail and the dayside magnetopause for example) the distance between the probes may be varied from a few kilometers to several Earth radii in order to discover the spatial and temporal scales of importance.

The Global Electrodynamics Mission will employ five spacecraft to provide an examination of the energy exchange processes between the ionized and neutral components of the upper atmosphere with a description of its global response recorded with remote-imaging techniques. Four identically instrumented satellites will be capable of in-situ sampling in regions below 200 km where energy and momentum are exchanged between the ionized and neutral gasses and where electromagnetic energy from the magnetosphere is ultimately dissipated as heat and light. With onboard propulsion, the four spacecraft will fly approximately along the same orbit with variable separations allowing spatial and temporal variations to be identified.

The Magnetospheric Constellation Mission will address the key question of the global evolution of small scale features into larger scale features in the magnetosphere. These questions are directly related to the response of the system to magnetospheric substorms and to the role small scale turbulence plays in large scale convection In order to accomplish this task, we must distribute in excess of 20 spacecraft into the magnetospheric volume in a manner that allows them to sequentially sample a small region in space while the orbits allow such sequential samples to be taken at widely separated locations. The power of a large number of samples is considerably enhanced by utilizing the capability to perform radio sounding between the spacecraft. Then tomographic imaging techniques can be utilized to describe the evolution of the plasma within the large volume bounded by the spacecraft orbits.

This report should serve as the initial step toward further mission refinements that will ensure the flight readiness of these missions within the next 5 years.

1. THE GEOSPACE ENVIRONMENT



Credit: K.Endo/Nikkei Science Inc.

1.1 Introduction

The geospace environment includes neutral gases, plasmas, energetic particles, and magnetic and electric fields within a broad region that extends from ~60 km to ~100 RE altitude. It is representative of a broad class of astrophysical systems involving the flow-induced creation of dynamic and hot magnetized plasmas and the subsequent interaction of that created environment with the surrounding medium of cooler gases and plasmas. We have learned that such environments generate a vast array of fascinating phenomena that includes the hyperacceleration of charged particles, beautifully structured optical and x-ray emissions, and powerful electrical discharges connecting vastly separated regions of space. We have also come to appreciate the practical importance to mankind of understanding these phenomena as realized in the geospace environment.

The starting conditions for the generation of the geospace environment include the Earth's magnetic field and neutral atmosphere, and the various emanations from the Sun, including the plasma solar wind, magnetic fields, and UV radiation. The atmosphere absorbs the UV radiation, becoming partially ionized and providing a lower boundary to our geospace environment. The magnetic field interacts with charged particles and the magnetic field from the Sun to form an outer boundary of the geospace environment called the magnetopause. The vast volume of geospace enclosing a fully ionized plasma in the magnetosphere, extracts electromagnetic and particle energy from the Sun, redistributes it, sometimes explosively, within the magnetosphere, and dissipates it as heat and light in the upper atmosphere. The energy conversion, transport, and dissipation processes are controlled by plasma phenomena that are applicable in a wide range of astrophysical conditions and are part of the unique environment of a planet that supports the evolution of life.

Charged particles in the geospace environment originate in the solar wind and are produced internally by the absorption of UV radiation from the Sun and by impact ionization interactions with other energized charged particles. The presence of the planetary magnetic field provides a natural magnetic bottle in which a significant population of the charged particles can be energized and trapped. The resulting charged particle radiations are a critical natural hazard to space-borne electronic systems and astronauts. Much of the energy processed by the magnetosphere is dissipated in the upper atmosphere, leading to modifications that are of practical importance to mankind. These include induced electrical currents that can damage power networks and pipelines, atmospheric heating causing huge increases in the drag on low-altitude space systems, and disruptions to HF and UHF communications, including critical navigation systems. For a world that is becoming increasingly dependent on globally distributed and space-based high technology infrastructures, it is becoming increasingly important that we understand the processes involved in the conversion, transport, and dissipation of energy in the geospace environment.

The processes that take place in the geospace environment are sensitive to long-term changes in the solar output occurring over time scales of many centuries. At the other extreme they are sensitive to short-term changes in the density and velocity of plasmas taking place over time scales of less than 1 second. The range of spatial scales is similarly vast, varying from the dimensions of the geospace environment itself (10's of Earth radii) to the motion of individual particles in the magnetic field (a few centimeters). What is more significant is that processes that operate at one temporal or spatial scale are invariably coupled strongly to processes that operate at very different scales. Strong cross-scale coupling, in part a consequence of the long-range nature of electromagnetic interactions, is apparently ubiquitous to space plasma systems and represents a fundamental impediment to characterizing the geospace environment with single satellite missions.

Further understanding of many important geospace processes will require multiple satellite missions with closely coordinated operations and orbital positions. To resolve the space-time ambiguities that have always been inherent in space plasma measurements, and to make the connections between processes acting over different spatial and temporal scales, it is necessary to make measurements simultaneously at multiple positions within the geospace environment. Because critical portions of the geospace medium are invisible to remote-sensing techniques, such measurements require the use of multiple satellites flying in close coordination with each other. While new techniques have been developed for the remote-sensing of space plasmas, forming the basis, for example, of the upcoming IMAGE mission, these techniques cannot sense many of the critical parameters that are needed to understand the processes operating within the geospace environment

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1.2 Basic Characteristics

Previous spaceflight missions devoted to exploring the geospace environment have provided a substantial framework describing different pieces of the geospace environment and have demonstrated the need to understand the connections between them. An important property of space plasma environments is the existence of nonlocal coupling processes. The motion of charged particles can produce currents and electric fields both of which produce forces that act remotely from the source region. The situation is further complicated by the presence of an external magnetic field which produces radical differences in the mobility of charged particles in the directions parallel and perpendicular to the field. In this case communication over vast distances is made by magnetic field-aligned currents and electromagnetic waves. These electrical connections can be established between plasma environments that are very different. Hot, fully ionized plasma in the magnetosphere is connected to relatively cold partially ionized plasma in the upper atmosphere. While we presently know that these connections exist, how the connections are established and maintained has yet to be discovered.

Present physical descriptions of the global flow of momentum and energy from the solar wind through geospace have relied primarily on relatively simple magnetohyrodynamic (MHD) fluid approaches. While these approaches allow a description of geospace like those shown in figure 1, the ISTP and FAST satellites have provided new insights into the complexity of this transport and underscore the processes operating on a spectrum of scale sizes (both MHD and sub-MHD) that complicate any simple fluid description. At present, we have a growing appreciation that structured, turbulent flows play an important, if not central, role in the transport. Turbulence is a feature likely ubiquitous in solar system and astrophysical fluids. The geospace environment provides a nearby laboratory where these naturally occurring processes of the plasma universe can be readily explored over a wide range of spatial and temporal scales.

At the outer boundary of the geospace environment, and deep within the tail of the magnetosphere, two fully ionized gases with different magnetic field configurations meet. This meeting place is the site of magnetic-field reconnection, where significant energy conversion and mass transport occur, and which are well documented

Figure 1. This MHD simulation of the magnetosphere illustrates spatial variations in density and boundary locations that additionally change in time.

from previous missions. However, the processes responsible for the observed phenomena, which are applicable in other astrophysical systems, have yet to be understood. Multipoint measurements are required to advance this area where the role of spatial and temporal gradients must be understood.

Within the magnetosphere, the plasma and magnetic field are highly variable, often responding in dramatic fashion to small changes in external forces. Small scale disturbances may expand to much larger scales and propagate from a small localized source to involve the entire magnetosphere. Not only have these propagation effects been observed at widely separated locations, but in the near future we will image the global response of the magnetosphere with NASA's IMAGE mission. Nevertheless, the conditions under which small perturbations will grow, and the mechanisms involved in their expansion, remain to be discovered. Such a discovery will require the deployment of multiple observation platforms that can provide an instantaneous picture of the field and plasma structure out to distances of many Earth radii.

At the inner boundary, the geospace environment is a partially ionized atmosphere that provides a medium in which electromagnetic and particle energy is dissipated. The particle energy originates from the magnetosphere. In specific spatial locations, or when the configuration changes, the magnetic field no longer efficiently traps the energetic particles in the magnetosphere. Then they may travel along the magnetic field and impact the atmosphere, producing excited species that radiate in the aurora.

The impact of these particles changes the dynamics and the conducting properties of the medium and this information is transmitted back to the magnetosphere, modifying its behavior. The dynamics of the upper atmosphere are also affected by the varying solar UV input and by the dynamics and chemistry of the lower atmosphere. This coupling between the upper and lower atmospheres may involve the propagation of waves from the surface and the human induced changes in the chemical composition of the atmosphere.

As a recurring theme it should be emphasized that while **previous missions have well exposed the connected nature of different regions of the geospace environment, the most effective mechanisms establishing the connections have yet to be understood. The hierarchy of spatial and temporal scale sizes involved in coupling processes leads naturally to a requirement for multiple point measurements with a variety of spatial and temporal separations.**

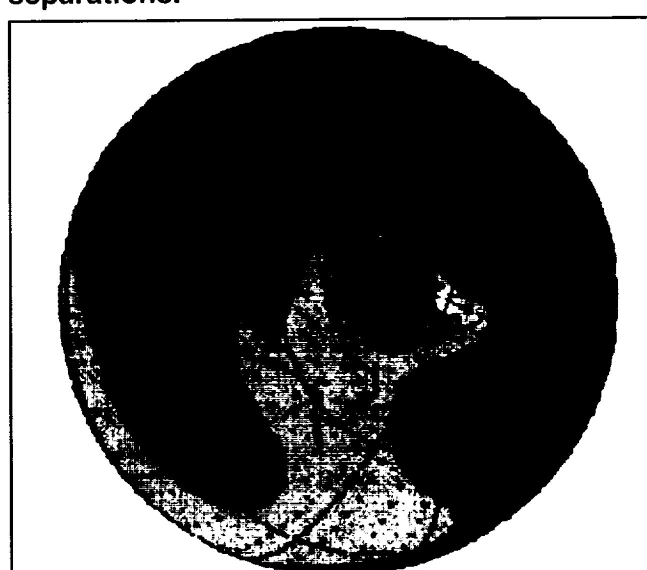


Figure 2. This simulation of the upper atmosphere winds and composition shows that inputs at high latitudes affect the entire global system.

2. SCIENTIFIC OUTLOOK

2.1 The Outer Boundary

The Bow Shock and Magnetosheath

The outer boundary of the geospace environment is important because all energy from the solar wind must flow through it. This region is complex because the interaction between the supersonic solar wind and the Earth's magnetic obstacle is decidedly nonlinear. Since the speed of the solar wind exceeds the speed of information traveling from the Earth telling the solar wind that the Earth and its magnetosphere are blocking the advancing solar wind, a shock wave forms that heats, slows and deflects the flow around this obstacle. Across the shock the magnetic field and flow are reconfigured so that the magnetic field drapes over the obstacle and the flow is diverted around it. Detailed observations show the bow shock is rarely, if ever, stationary. Thus, information on the global state or position of the bow shock and magnetosheath is difficult to deduce from single point observations.

The properties of the solar wind undergo both slow and abrupt changes as the solar wind moves toward the outer boundary of the magnetosphere, the magnetopause. The bow shock, across which the first jump in properties occurs, is a fast magnetosonic wave. Two other waves exist in a magnetized plasma that also can cause abrupt changes in the plasma. These waves propagate more slowly so that they stand in the flow closer to the obstacle. They are the Alfven wave, that rotates the magnetic field direction, and the slow-mode wave, that compresses the plasma but rarefies the magnetic field. All these processes act to change the properties of the plasma as it moves through the region between the shock and the magnetosphere called the magnetosheath.

The formation and the evolution of the series of the standing waves between the bow shock and the magnetopause requires more quantitative studies. Numerous observations of a slow-mode transition upstream of the magnetopause with large density enhancements and with weakening and bending of magnetic field lines were made from the ISEE spacecraft. Regions of enhanced and reduced magnetic pressure were interpreted as standing slow-mode structures. The pile-up of magnetic field adjacent to the day side magnetopause squeezes the plasma out of the region resulting in a low-density region.

As we place more and more sophisticated technological systems in space ***it is becoming more and more imperative to determine how the magnetosphere reacts globally to the passage of interplanetary disturbances*** such as coronal mass ejections or interplanetary shocks. Yet it is only after these events have been processed through the shock and the magnetosheath, that the inner magnetosphere, ionosphere and thermosphere react to them. Thus, ***it is essential that the properties of the bow shock and its influence on the plasma in the magnetosheath be understood.***

The Magnetopause and Reconnection

The magnetopause, which is the boundary layer between solar plasma and the Earth's magnetic field, is in constant motion, controlled by the solar wind dynamic pressure and by the southward component of the interplanetary magnetic field (IMF). An increased solar wind pressure compresses the magnetopause and moves it Earthward while the southward interplanetary magnetic field removes flux from the day side and adds it into the tail magnetosphere.

The solar wind magnetic field produces a tangential stress by linking up with geomagnetic field lines across the magnetopause in a process known as reconnection. Throughout most of the volume of space, magnetized plasmas are fairly uniform along the magnetic field and therefore act as perfect electrical conductors. This high electrical conductivity minimizes any electric fields along the magnetic field and the plasma and field move as a unit. Thus the magnetic field is said to be frozen into the plasma. Reconnection, however, allows electric fields to appear along the magnetic field in a thin boundary region and the magnetic field is no longer frozen into the plasma. Linkage of the magnetic field across the magnetopause allows the solar wind plasma and magnetospheric plasmas on these field lines to mix and to be accelerated tailward above and below the magnetosphere. Once the field and plasma reach the tail region they are added to the magnetotail. The net result of dayside reconnection is to transport magnetic flux from the dayside to the tail. This alters the shape of the magnetosphere, the magnetic flux content of the tail, and the energy content of the tail.

Observations at the Earth's magnetopause indicate that magnetic reconnection is time dependent and exhibits significant three-dimensional effects. Several models of the time dependent reconnection include bursty single X-line reconnection, multiple X-line reconnection, and intermittent patchy reconnection. The three-dimensional topology results in the formation of magnetic flux ropes with multiple reconnection sites, and strong tube-aligned flows are expected to result from the reconnection. The reconnection is also associated with plasma acceleration events in the dayside magnetosphere. Inclusion of 2-D and 3-D effects is necessary to properly model the reconnection process. However, ***present observations are insufficient to assess the relative merits of different models.*** To answer questions on reconnection, flux transfer events, and ultimately energy flow and solar wind plasma entry into the magnetosphere, the large-scale structure of the magnetopause needs to be determined, in addition to the microscale processes that act within it. The magnetopause is a very thin boundary and is difficult to study without a carefully designed observational program consisting of multiple, strategically instrumented probes. The key outstanding question in this process is what controls the rate at which energy coupling takes place. ***What processes produce particle acceleration in the current layer known as the magnetopause?*** Does the microscale control the dynamics of the macroscale processes in the magnetosphere? This same question is outstanding and important in the dayside magnetopause at low latitudes and at high latitudes. Allied with this question is the problem of the source of the magnetospheric boundary layer. Again, are microprocesses controlling the entry of plasma into the magnetosphere, and if so are they processes such as diffusion or is the magnetic reconnection process in some way responsible?

While the boundary layer is one region in which mass gains entry into the magnetosphere from the solar wind, the polar cusp, the weak-field region of the Earth's magnetosphere is another. This region is also poorly understood, especially concerning the role of microphysics and macrophysics in determining the entry of plasma into the magnetosphere. Finally, there is the coupling of these stresses from the outer boundary of the magnetosphere to the ionosphere. If the magnetic field lines are equipotentials then field-aligned currents arise along them and the stress can be transmitted by the closure currents in the ionosphere. However, if micro instabilities arise in these currents, parallel electric fields can be present that allow the decoupling of these regions. This is another region in which ***cross-scale coupling of magnetospheric processes may control the dynamics of the magnetosphere.***

2.2 The Interior

The interior of the geospace environment, the magnetosphere, is a vast region extending from about 500--1000 km altitude out to distances of 10 Earth radii on the sunward side of the planet and to 50 Earth radii and beyond on the nightside. In this region the magnetic field geometry changes dramatically from a dipole geometry close to the Earth to a highly variable and stretched configuration in the tail. The plasma populations likewise change dramatically, from a dense very low energy gas near the Earth, to a more tenuous but highly energetic plasma at greater distances. Exchange of energy between the magnetic field and the plasma may take place very rapidly and is the most important feature that determines the distribution of energy within the system. Yet the conditions under which such energy exchange occurs, and the resulting evolution, escape our understanding.

The Quiet-time Plasma Sheet

The plasma sheet and particularly its central portion, the current sheet, are the most dynamic regions of the magnetotail. It is there that the currents supporting the antiparallel fields of the magnetotail lobes are confined. It is there that the energy imparted to the magnetosphere from the solar wind, and stored in the form of magnetic energy in the Earth's magnetotail, gets transformed into particle energy and affects the auroral ionosphere, the ring current, and the environment near geosynchronous orbit. Although the ultimate source of energy is the solar wind, ***the transfer of that energy to the plasma sheet particles is not well understood.***

It is during times of magnetic activity associated with substorms that the magnetosphere undergoes its most radical changes and that coupling between the magnetosphere and the ionosphere is manifested in enhanced currents and auroral activity. However, in order to determine the physical processes at work during such times, it is important to understand the plasma sheet configuration and the physical processes that operate at other times.

At times of steady but moderate solar wind energy coupling to the magnetosphere, magnetospheric circulation is thought to reach a state for which all indicators of substorms show quiescence, yet polar cap circulation continues at a steady and moderate level. Limited information from single point measurements in the plasma sheet suggests that convection in the tail is unsteady despite the overall stability of the global circulation of magnetic flux and particles.

In order to characterize this state of the plasma sheet, correlative measurements at many points of the system are necessary in order to measure the spectrum of scale sizes in the plasma sheet flows.

Magnetospheric Currents and Magnetic Field

Statistical averages of plasma and magnetic field measurements provide average descriptions of the system that often deviate considerably from the instantaneous measurements, thus suggesting that *the* ***system is far more complex than the average models would suggest.*** It is impossible for a static model parameterized on global indices to capture the complexity, the richness, and the physics of the instantaneous magnetospheric configuration. Even global MHD models are presently unable to reproduce the spectrum of fluctuations that are seen in the data. In order to describe correctly the variations, and to present the appropriate challenges to theoretical and modeling efforts, ***it is essential to separate spatial from temporal variations.*** Multipoint measurements of the plasma distribution functions and the magnetic field would allow the spatial and temporal scales over which changes occur to be determined and the self-consistency between the current distribution and the magnetic field to be established.

The Tail Current Sheet

The current sheet is a most important feature of the magnetosphere since it supports the magnetic field geometry of the tail, provides the environment within which magnetospheric plasma is accelerated, and undergoes the dynamic changes that precede and follow a magnetic substorm. Knowledge of the thickness and variability of the current sheet is essential for an accurate description of the plasma energization processes in the magnetosphere and even more critical to our understanding of the substorm process by which energy is dramatically redistributed in the geospace environment. The current sheet behavior during times of relatively steady convection is poorly understood. It is apparently quite thin, but embedded in a much thicker plasma sheet that allows convection to proceed in the absence of substorms. The only possible way to ensure that the tail current system is adequately diagnosed, at the time and place where it actually becomes unstable, is to simultaneously and continuously measure its properties at many different downtail distances. This necessitates a constellation of satellites with separations along all three spatial dimensions. Modeling and data assimilation of field and plasma properties can result in an image of the magnetosphere beyond that achievable from the measurements alone.

Particle Acceleration

The continuously changing magnetic field configuration, and electric fields inside the magnetosphere, result in a wide variety of mechanisms that can accelerate charged particles. These particles move around the magnetosphere, changing the magnetic field and current distributions, and thus changing the acceleration processes. In addition, field-aligned currents may serve to connect the magnetosphere to the ionosphere, resulting in field-aligned electric potentials. ***The mechanisms that produce field-aligned electric potentials and their role in accelerating magnetospheric particles are poorly understood at***

present and yet they are a critical element in the coupling between the magnetosphere and the ionosphere. In addition to unfolding the processes that act to maintain a balance between the particle and magnetic pressures in the magnetotail, it is also necessary that the dramatic evolution of these processes during a substorm be understood.

The three-dimensional circulation of the substorm-accelerated particles has not been clearly resolved. Although single particle descriptions have led to certain predictive pictures of the spatial profiles of plasma sheet pressure, temperature, and density, such profiles have not been verified by measurements. In fact, there is evidence from statistical averages that some of the predicted pressure and temperature may not be present. A resolution of these problems requires that the system and its evolution be observed at many points simultaneously over a wide range of external conditions.

Magnetospheric Substorms

One problem has been central to magnetospheric physics for 30 years, yet still remains largely unresolved, that of how magnetic-field energy is converted into plasma-kinetic energy and thermal energy during the course of magnetospheric substorms. The evolution of the magnetosphere during the course of a substorm is of primary interest to the space/physics community. Our lack of understanding is due in part to attempts to piece together a global picture from single-point measurements of different substorms. Substorms result in an explosive release of energy and no two substorms are alike. We have amassed several large data sets, we have diagnosed several aspects of substorms, and we have developed several models of substorms. ***What we do not have are simultaneous, multipoint observations of several substorms*** that would allow us to determine the chain of events leading up to a substorm and the chain of events during a substorm, which in turn would allow us to understand the global evolution of the magnetosphere and to evaluate the various substorm models.

It is known that the magnetosphere changes prior to a substorm in response to magnetic flux added to the lobes: the plasma sheet thins and currents intensify. Substorm onset marks a rapid change in the magnetospheric topology and an explosive release of energy. Several fundamental questions about substorm physics are outstanding. What is the morphology of the magnetosphere when a substorm starts and how does the morphology evolve during the substorm? When and where does reconnection start in the magnetotail, how important is it, and how does it evolve as the system evolves? How does the magnetotail current system evolve prior to and during a substorm and how does this current system relate to auroral activity in the ionosphere? What are the natures of plasma flows during substorms and of particle acceleration during substorms? The answers to these questions await multipoint measurements.

Connection to the Aurora

In the magnetotail, at distances near 15 RE from the Earth and close to the neutral sheet, fast plasma sheet flows are responsible for most of the plasma sheet energy, particle and flux transport. Whether these fast flows can account for the energization of the near-Earth environment and the ionosphere during substorms is not presently known due largely to our inability to resolve temporally and spatially the three-dimensional structures involved in diverting the neutral sheet current through the ionosphere in the so-called substorm current wedge. The ISTP measurements are providing some direct measurements of the cross-tail localization of this process and a glimpse of the complexity and richness of the magnetotail plasma when studied at small spatial scales. However, ***a sensible understanding of this critical coupling process between the magnetosphere and the ionosphere cannot be achieved without appropriately distributed measurements.***

The prevailing understanding is that the current wedge maps to the entire width of the aurora and that its outermost boundary is the location where the current feeds from the magnetosphere to the ionosphere. Thus, it is a very important key in the chain of energy transport from the plasma sheet to the ionosphere. Understanding the three-dimensional evolution of the substorm current wedge system promises to solidify estimates of the magnetospheric-ionospheric energy coupling during a substorm and in addition probe simultaneously its component activations and their ionospheric mapping.

2.3 The Inner Boundary

The thin envelope of neutral and ionized gases that surround our globe, the Earth's upper atmosphere, becomes a critical sink for energy and momentum sources from both above and below this region. In this lower boundary region of geospace many individual mechanisms for dissipation and transport of energy have been identified. However, the relative importance of the many processes, and the different spatial and temporal scales over which they operate, still elude our understanding. ***The largest impediment to progress in our understanding in these areas is the lack of data gathered simultaneously at several points in space.***

Solar UV Energy

UV energy from the Sun creates the ionosphere and affects the chemistry of the various species whose populations depend on the balance of competing production and loss mechanisms. Although the basic chemistry is understood, the energy balance associated with this fundamental process is not. For example, one third of the solar energy associated with the UV ionization process appears as a form of kinetic energy associated with newly liberated electrons which eventually is transferred to the neutral gas. As there are no reliable measurements with which to measure and understand this flux, the extent to which such suprathermal electrons contribute to any dayside heating, plasma oscillations, and current systems remains largely speculative.

Heating by Auroral Particle Precipitation

Scientific experiments have established the mechanisms by which energetic precipitating electrons interact with neutral particles in the upper atmosphere to produce the visible light emissions known as the aurora. Within this interaction, "thermal" electrons are created and neutral gases are heated and ionized. The consequences of these newly created regions of high conductivity and heated gases are not well understood

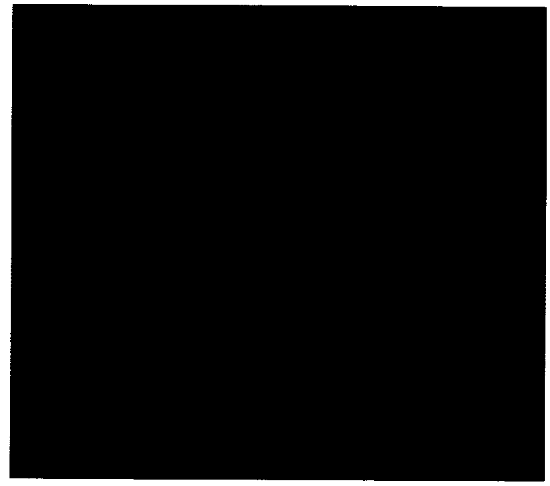


Figure 3. This auroral image shows a multiplicity of spatial scales that exist.

because the aurora is highly variable. It involves a large range of distance scales, and is governed by electric fields which vary at their source in the magnetosphere and are controlled locally in the upper atmosphere by the newly formed high conductivity regions. Such fields not only govern the motions of ionized gases, which in turn create large-scale winds, but also critically affect the production rates of numerous ion species. As a consequence, the time constants for cooling and transport mechanisms of the upper atmospheric gases become highly nonlinear in these regions. ***How the upper atmosphere responds as a system to such localized and rapidly varying auroral arc formations and electric fields remains a fundamental unanswered question in the solar-terrestrial chain of energy transfer and dissipation.***

Joule Heating

Besides heating caused by the kinetic energy of precipitating auroral particles, the upper atmosphere is also heated by the electromagnetic energy of magnetospheric origin delivered by field-aligned currents and Alfven waves. This Joule heating may be shown to be proportional both to the relative difference of the ion velocity and the neutral wind and to the local conductivity, and thus is highly altitude-dependent. Whereas such heating may be easily evaluated for "steady state" conditions, the auroral region is highly variable and

and thus our understanding breaks down, since the time constants for the resulting localized Pedersen conductivity regions and neutral winds differ from those of the highly variable magnetospheric electric fields. Furthermore, such variations exist over critical vertical distance scales for which the altitude of maximum conductivity depends on the impinging charged-particle energy which is also highly variable.

Evaluating the interplay of the variable conductivity and electric fields over a large range of spatial and temporal scales, as well as evaluating their nonlocal effects, is the next logical step to progress in our understanding in this area.

Energy Conversion Between the Ion and Neutral Gases

Although the ionized and neutral gases within the upper atmosphere are subject to different forces and boundary conditions, the movements of these gases are coupled through ion-neutral collisions. Thus, at high latitudes, the ions are set in motion by large magnetospheric electric fields which in turn set the neutral gases in motion. At middle and low latitudes, the neutral gases are set in motion from solar heating and they, in turn, drag the ion gases, which set up electric fields through differential forcing. What may appear to be a simple "cause and effect" relation between the two coexisting gases is actually far more complicated because the neutral gases tend to be sluggish, whereas the direction and speed of the ionized component responds quickly and efficiently to rapid variations in the driving electric field. The ion velocity also includes a broad range of scale lengths that are involved with this "convection." ***How the two gases couple, and over what temporal and spatial scale lengths this coupling is most efficient, remains one of the outstanding fundamental questions in upper atmospheric physics today.***

Plasma Wave Instabilities and Heating

Another form of energy dissipation takes place in the form of instabilities and turbulent mixing. Such instabilities exist for both the ionized (e.g., two-stream, Rayleigh Taylor, gradient drift) and neutral (e.g., acoustic waves) gases and include important effects on boundaries, gradients and localized heating. The key to understanding the importance of energy dissipation in these processes again falls upon our knowledge of how the energy is distributed among the various scale lengths inherent to both gases. Although there may be more energy at longer scales, coupling efficiencies may be greater at shorter scales, for example, when the wavelength equals a gyro radius. In addition, different dispersion relations enable energy to grow more efficiently at different scales. The interplay between growth rates and dissipation processes eventually determines whether a set of instability processes becomes highly turbulent (e.g. "Spread-F" instabilities at the magnetic equator), or maintains a predominantly coherent-like nature (e.g. two stream waves in the auroral and equatorial electrojets).

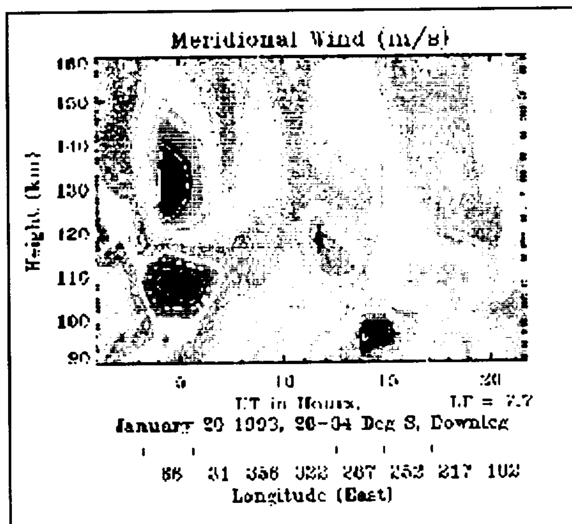


Figure 4. Wind data from the UARS satellite shows evidence for large scale waves that can propagate to altitudes above 150 km.

Gravity Waves and Tides

Gravity wave energy originating from below the upper atmosphere, coupled with tidal motions within the upper atmosphere, create a highly complex set of oscillations that exist on both global and mesoscales at all latitudes. Such energy sources have been observed along one-dimensional in-situ trajectories, and more commonly, for an extended period of time at a single location using observations obtained with ground-based equipment. However, the global distribution of such processes, how they affect the local neutral and ionized number densities, and over what scale lengths, remains largely unexplored in any systematic way. For example, gravity-wave breaking clearly involves highly nonlinear interactions and a global data base is needed to evaluate the resulting dissipative processes associated with such events.

Electromagnetic Wave Energy Originating From Thunderstorms

Another form of energy that penetrates the Earth's upper atmosphere originates from the upwards propagation of electromagnetic pulses and storm-time electric fields associated with lightning and weather systems. Such electric field pulses have been shown to include a large component parallel to the magnetic field and thus may be expected to transfer their energy via a process that heats the local gases. The existence of such fields of tropospheric origin in the upper atmosphere results mainly from a series of exciting new discoveries carried out in the last 10-15 years. The extent and importance of such dissipation effects, however, are currently still not known. Transient thunderstorm-related electric fields exist in localized "clusters" (of 100--1000 km typical widths) that track the storm cells and may provide important seasonal adjustments to the energy balance of the Earth's upper atmosphere.

3. WHAT ARE THE ISSUES?

From the preceding discussion it is apparent that our present understanding of the geospace environment is inadequate in a number of areas. Previous observational programs have combined with theoretical developments and computer modeling to provide an excellent description of most of the physical processes that can take place in the environment. Single-point measurements, and fortuitous multipoint measurements, have verified that many of the processes we believe could take place, probably do take place. Our goal must be to determine the relative importance of the various processes, the conditions for onset of the processes, and the spatial and temporal scales over which they evolve.

Answers to these questions are not just idle curiosities. Rather, they directly affect our ability to assess the vulnerability of biological and human-made systems in space. As humanity becomes increasingly more reliant on space based systems it is essential that we advance our understanding of the environment in which they operate. In doing so we will fulfill two significant objectives: (1) to protect our space based systems in which we have so much invested, and (2) to advance our understanding of the properties of geospace that make it the unique environment it is for supporting a habitable existence.

In the following sections we will identify specific science questions that are each most effectively addressed with specific multiple satellite configurations. These questions involve the entire geospace environment and it is not sensible to expect that a single mission will efficiently address all the questions. However, the problems divide rather naturally into three areas.

The lower boundary of the geospace environment provides the region for dissipation of the energy extracted from the solar wind and transported through the magnetosphere. Presently we do not know the important spatial and temporal scales for the dissipation processes. Yet these processes lead to changes in atmospheric composition, heating, and plasma transport parallel and perpendicular to the magnetic field that must be understood to determine their contribution to the long-term stability of the atmosphere. In the short term, changes in the atmospheric density and composition can lead to unpredictable orbital perturbations affecting the lifetime of satellites. Variable plasma transport processes provide the seeds for ionospheric instabilities that degrade the propagation of radio signals. It is important that we understand these effects well enough to evaluate the vulnerability of space-borne navigation and communication systems.

In the magnetosphere the magnetic field and plasma conditions frequently undergo rapid and significant variations. The physical processes that mediate these variations are applicable to many other astrophysical situations and can be quantitatively observed. The magnetosphere provides an important location where measurements can be used to evaluate or constrain theories that reach beyond the geospace environment into the evolution of the plasma universe. In addition to this rich research tool, the magnetosphere is also the source of electric fields and energetic particles that modify the upper atmosphere. It is the region in which trapped particles can reach very high energies and be transported rapidly to widely separated locations producing hazardous environments for geosynchronous satellites and other orbiting vehicles including the space station and the space shuttle. It is essential that we understand the energy conversion and transport processes well enough to quantify and ultimately predict these hazards.

What we understand so far is that the geospace environment is not a simple linear system. Its large-scale configuration and response are not simply related to the external conditions, suggesting that the immediately previous state needs to be taken into account and that the role of coupling between scale sizes needs to be understood. These are the directions that future exploration must take in order that we understand our environment well enough to make sensible comparisons with other planetary environments, to determine the vulnerability of human systems that are placed within it, and to assess the location of the Earth in its evolutionary journey.

4. WHY MULTIPROBE MISSIONS?

The most important questions to be addressed underlie three requirements that must be fulfilled with new missions of understanding.

4.1. Removal of Space and Time Ambiguities

The geospace environment is constantly changing in response to internal and external forcing. This environment contains very large spatial gradients that delineate boundaries between plasma and neutral gas regimes with quite different properties. These differences may lie in the temperature, the velocity, the density, and the composition of the charged and neutral species. The boundaries may also mark changes in the configuration of the magnetic field including the bow shock and the magnetopause. The most important point to note is that in addition to changes in the parameters themselves inside the regions separated by boundaries, the boundaries themselves are very dynamic. Thus, in any given observational circumstance, it is necessary to know if changes are effected by a change in the location of a boundary with respect to the observer (a spatial change) or a change in the properties within a given region (a temporal change). Such a resolution can only be obtained with the use of multiple platforms. A brief discussion concerning the required number of satellites is in order. If a discontinuity, such as those found in the solar wind, is being carried past a set of satellites, then four spacecraft are needed to define the orientation and velocity of the feature using only the times of observation at each spacecraft. The feature must be essentially flat for such a description to be helpful, i.e., it must have a radius of curvature that is large compared to the separation distances between the satellites. If some simplifying assumption can be made, such as the absence of gradients along the magnetic field direction, then the number of observations can be reduced. If, however, the scale sizes of the changes are comparable to the separation of the satellites, then the number of observations required increases. For example, if one radius of curvature of a structure is small, such as in a magnetic flux tube, then five observations are needed to determine unambiguously the velocity and orientation of the structure. If the structure has two small radii of curvature such as an ellipsoid, then six observations are needed. If temporal variations are possible, a seventh vehicle is required. If instead of describing a localized structure, one needs to pixelate a volume of space in order to visualize the otherwise invisible processes occurring within the volume, the number of observing sites required becomes even larger. Assimilative modeling provides an important tool for use in extending the detail available from individual pixel measurements. In this case the cost-effective implementation of the mission depends on our ability to design a sufficiently self-correcting assimilation procedure based on what we learn about the degree of reproducibility in the measurements.

4.2. Observations of Micro- and Macro- Scale Phenomena

Throughout the geospace environment there is strong evidence for links between large- & small-scale processes. Many plasma instabilities require the presence of large-scale gradients to produce smaller scale gradients. The dissipation of heat and momentum at small-scale sizes induces larger-scale motions in response to the pressure gradients that are created. If we are to identify important physical relationships between processes that act at quite different spatial and temporal scales, then observations must be made simultaneously at all the scale sizes thought to be relevant. This requirement can be met in several ways that are dependent on the information required. For example, the onset of small-scale processes and their evolution may be studied with global context supplied by imaging the large-scale configuration of the magnetosphere.

However, the association between two widely separated small-scale processes would require the deployment of, and simultaneous observations from, two or more groups of observational vehicles.

4.3 Global Coverage

The wide range of spatial scales over which the thermosphere, ionosphere, and magnetosphere interconnect make it a fundamental priority that we move toward the goal of simultaneously observing the system at all spatial scales of importance. The physical size of the system requires multiprobe measurements to accomplish this goal. In this report we will discuss multiprobe missions that will provide foundations for the future. The scope of these missions is limited by considerations of available technology and cost, which drive us toward present capabilities that can be achieved utilizing a single launch vehicle. In the magnetosphere, this limitation applies principally to the number of spacecraft that can be deployed but not to their location. In the ionosphere and thermosphere this limitation applies largely to the local time distribution of the probes. The purpose of this report is therefore to provide a base from which the first multiprobe mission definitions can be refined and also to provide some scientific vision that establishes the need to extend the multiprobe context into the deployment of uniformly distributed observing platforms in space.

It is most important to note that ***critical steps forward cannot sensibly be made without consideration of the deployment of multiple observation platforms into geospace.*** While this has long been a desire, the availability of new technologies applied to instrumentation, satellite manufacturing, and propulsion systems, now make possible the required advances in scientific knowledge.

5. TECHNOLOGY AND SCIENCE NEEDS COMBINE

It is important to understand that the need to separate space and time variations has been appreciated for many years. Similarly, the need to understand the coupling between physical processes that act over quite different space and time scales, has also been appreciated. While previous observational missions have been undertaken, and the precise measurements required to constrain physical theories have been exposed, our discipline has also seen a revolution in the capabilities of space instrumentation, space flight materials, and expected launch capabilities. Furthermore, computational speed, storage media, and data access capabilities, which are all critical factors in assimilating and interpreting the vast amounts of data that will be provided by the multiprobe missions, have undergone great advances in the past 10 years and are likely to improve even further in the near future.

The importance of advanced technology developments and applications cannot be over emphasized. Now it is possible to construct sophisticated instrumentation in a relatively small volume so that the capabilities of a single satellite payload are significantly increased. The same reduction in size and mass of the instrumentation also applies to many spacecraft subsystems and thus the overall size of the satellite is reduced. High-capacity solid-state memory systems allow data sampling rates to be very high and radiation-hardened digital signal processors allow sophisticated data analysis and reduction procedures to be conducted onboard. Combined with innovative carrier systems and deployment techniques, it is possible to carry many satellites into orbit on a single launch vehicle. At high altitudes new miniature thruster systems can be used to dramatically change the orbits of satellites. At lower altitudes thrusters can be used to accurately maintain satellite orbits and relative positions.

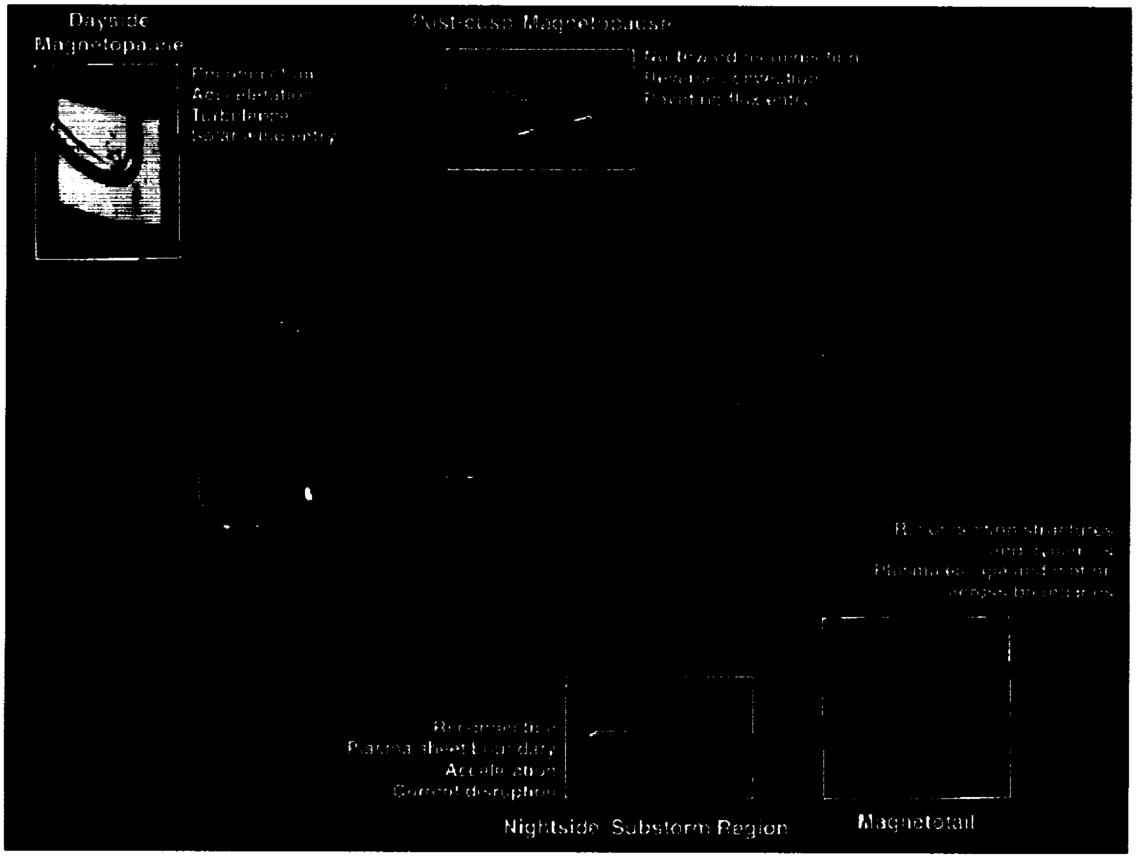
With these improved capabilities the space science discipline is poised to make the next dramatic step toward significantly improving our understanding of the environment of the Earth and other planets. These dramatic steps are enabled by the unique ability of simultaneous measurements in space to separate ambiguities that have until now hidden the relative importance of many physical processes.

6. MULTIPROBE MISSIONS

The need to resolve spatial and temporal ambiguities, and the need to establish the coherence lengths for many physical processes in the geospace environment, drive the need for multiprobe missions. There are many multiple satellite configurations, deployed in a variety of ways, that could be utilized to attack specific problems. Each mission varies in its complexity, number of satellites, and number of launch vehicles, and hence the range of desirable scenarios covers a wide range of total costs. The science definition team has considered three solar-terrestrial probe-class missions that will produce a solid foundation upon which future multiple satellite configurations can rest and from which we can learn.

A Magnetospheric Multiscale Mission will examine critical boundaries in the magnetosphere with spatial scales from kilometers to several Earth radii. The low-altitude extent of the geospace environment will be investigated to understand energy dissipation in the upper atmosphere by the Global Electrodynamics Mission. The processes mediating global transport of energy and momentum in the magnetosphere will be investigated by the Magnetospheric Constellation Mission.

6.1 MAGNETOSPHERIC MULTISCALE MISSION
Understanding Fundamental Processes at Space Plasma Boundaries

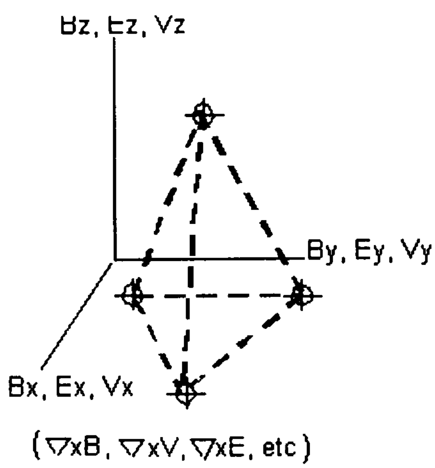


MMS Summary

Space plasma science and technology have achieved levels of maturity that now allow us to turn away from phenomenology and towards fundamental understanding. ***The Magnetospheric Multiscale (MMS) Mission is focused on understanding the fundamental plasma processes that operate at space plasma boundaries and current sheets.*** Plasma processes at boundaries transport, accelerate and energize plasmas, and by doing so ***control the structure and dynamics of the Earth's magnetosphere and related astrophysical plasma environments.*** The MMS Mission will measure three dimensional (3-D) fields and particle distributions and will measure and discriminate their temporal variations and 3-D spatial gradients, with high resolution, while ***dwelling in the key magnetospheric boundary regions ranging from the subsolar magnetopause to the distant tail.*** It will separate spatial and temporal variations over scale lengths appropriate to the processes being studied - connecting the small-scale kinetic regime to the larger-scale regimes appropriate for magnetohydrodynamic (MHD) calculations. The MMS ability to separate spatial from temporal effects, and its ability to measure gradients, are the critical missing links of previous missions that will allow MMS to dramatically enhance our understandings of these fundamental processes.

The MMS Mission consists of both a "telescope" and a "microscope." The MMS telescope consists of two small microsats in elliptical orbit that will provide global stereo ENA imaging to provide the context of large-scale dynamics. The heart of the MMS Mission, its microscope, is a boundary layer probe consisting of ***four identical spinning spacecraft (s/c), flying in a tetrahedral configuration with spacing variable from less than 10 km to several Re.***

Each s/c will contain an identical set of 3-D instruments with high angular and temporal resolution (plasma electron and ion composition, energetic electron and ion composition, magnetometer, electric fields and waves). Interspacecraft VHF ranging will determine s/c spacing and allow trigger mode burst high rate data recording on all s/c for maximum resolution of boundaries or events. Onboard propulsion will allow the orbits of the MMS "probe" to have four separate mission phases covering almost the entire magnetosphere, from the near-Earth equator to the magnetotail. In each phase the 4-s/c "probe" will dwell at apogee in key boundary regions of magnetic reconnection and energy conversion.



MMS Mission Description

The Earth's magnetic canopy or magnetosphere acts both as a shield against the solar particle flux and as a storage reservoir for energy extracted from the solar wind flow. The coupling between the solar wind flow and the magnetosphere, and the transport of energy within the magnetosphere, appear to be controlled by processes occurring in a number of thin boundary regions that separate vast and topologically distinct volumes of magnetospheric plasma. Models (sometimes conflicting) exist for some of these controlling processes, but they fail to uniquely identify the kinetic processes responsible for dissipation, they fail to connect the small-scale (kinetic) to the larger-scale MHD processes, and they are not adequately testable using existing data sets. As a result of the Magnetospheric Multiscale Mission we will be able to understand how the magnetosphere is energized by the solar wind and we will be able to develop quantitative models based on first principles that predict the energy transfer. Through the detailed, highly coordinated measurement of particles and fields, MMS will determine with unprecedented resolution the microscale and mesoscale spatial properties of space plasmas in the key magnetospheric boundary regions.

For the first time we will measure in detail the physically relevant properties of magnetic reconnection in its various guises, which is the primary process that couples solar wind plasmas and fields into the Earth's magnetosphere, and which converts magnetic field energy density to particle energization inside the magnetosphere. Magnetic reconnection will be directly observed in each of the regimes where it is thought to occur around the Earth, including both the magnetopause and the magnetotail. This process is vital for transferring energy from magnetic fields to plasmas, and for coupling different regimes. It is central to many astrophysical theories, yet its operation in collisionless space plasmas is very poorly understood (as with other boundary processes, the kinetic processes responsible for the dissipation, and the connection between kinetic and larger-scale processes, are not known). We will quantitatively characterize the acceleration of charged particles to high energies in different distinct magnetic geometries. We will uniquely specify the spatial and temporal properties of plasma waves and turbulence which are of significance in many cosmic settings. Finally, we will be able to study the stability and dynamics of plasma structures over a remarkably wide range of parameters. The MMS Mission represents a major evolutionary leap beyond the pathfinding ESA Cluster Mission. Whereas the ESA cluster spacecraft are four independent spacecraft which fly in formation in a single operational orbit designed to study the bow shock and the cusp, the insitu probe part of MMS is a cluster of four electronically tethered, inter-communicating spacecraft designed to use orbit adjustments to study controlling boundary processes throughout the entire magnetosphere.

Key Science Questions

- o How do microscale processes near plasma boundaries couple to larger-scale dynamics and structures?
- o What controls the transport of magnetic fields, and thus energy, across plasma boundaries?
- o How are electric currents generated at boundaries to influence distant magnetospheric regions?
- o How do processes at plasma boundaries accelerate charged particles?

Required Measurements

Table 1 provides a description of the measurements required at four separate closely spaced points to determine the 3-D structure and dynamics of the key thin magnetospheric boundaries. The data must be properly synchronized between each spacecraft and must be sampled at a rate consistent with resolving spatial scales down to, for some regions, a few kilometers.

A proper understanding of the physical processes at work in different boundary regions requires 3-D measurements of the particle distributions and the electric and magnetic fields. From the measured gradients and curls of the fields and particle distributions, spatial variations in currents, densities, velocities, pressures, and heat fluxes can be calculated. Finally, identification of particle acceleration processes and regions where anomalous transport of charged particles is taking place will be uncovered through measurements of ac electric and magnetic field emissions.

In addition to these insitu measurements of essential plasma parameters, a global context for these measurements is required to assess the degree to which the mesoscale and microscale processes might regulate or be regulated by the global scale configuration and dynamics of the magnetosphere. This will be obtained by two small microsatellites dedicated to energetic neutral atom (ENA) imaging of the magnetosphere, and access to other space and ground-based imagers and monitors. The ENA imagers, measuring remotely the spatial, energy, and compositional distributions of the > 5 keV ion populations that generate the ENAs earthward of 10-12 RE, will complement any existing ENA imaging missions (IMAGE, Twins) by viewing the plasma dynamics from a near equatorial perspective. This perspective, for example, will increase the probability of viewing topology changes associated with reconnection and/or related processes in the near-Earth magnetotail. The ENA imaging satellites will remain in their insertion orbits of ~12 RE apogee and ~28 degree inclination throughout the mission. Stereo imaging is achieved by means of the natural random positioning of the two spacecraft on the same orbit trajectory. The ENA imagers will be sensitive to ENA intensities < 1 (cm2.s.sr.keV)-1 for accumulations of ~10 min [strong magnetic storm intensities have intensities

Table 1. Required Measurements for Magnetospheric MultiScale Mission

Parameter	Range	Accuracy
Electric Field Vector	-500 to 500 mV m $^{-1}$	±0.5 mV m $^{-1}$
Magnetic Field Vector	-1000 to 1000 nT	±0.1 nT
Magnetospheric Plasma	1 eV - 30 keV	± 10 %
Energetic Particle Distribution	30 keV - 3 MeV	± 5 %
AC Electric Field 100 Hz to 1 MHz	10^{-6} (V/m) ^{2} /Hz to 10^{-16} (V/m) ^{2} /Hz	± 5 %
AC Magnetic Field 100 Hz to 100 kHz	10^{-6} (nT) ^{2} /Hz to 10^{-16} (nT) ^{2} /Hz	± 5 %

> 1000 at lower altitudes] with angular resolution capabilities of < 4 degrees.

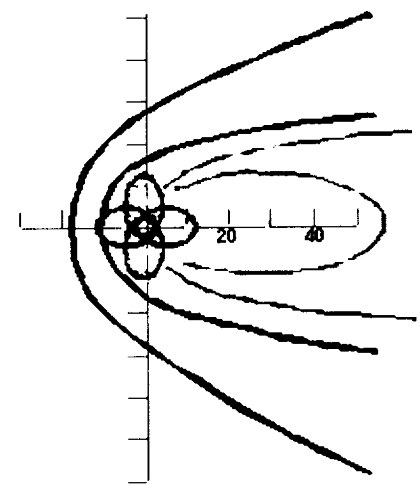
The Magnetospheric Multiscale Mission will also be conducted in concert with vigorous support from computer modeling and simulation activities. The MMS Mission's multiscale measurement strategy is ideally suited to the next generation of global magnetospheric simulation codes, which will have the capability of incorporating the more detailed physics of magnetospheric boundary layers. This advance in computational physics will allow an unprecedented closure between observations and theory on multiple scales, with physical insights that will be applicable to many other astrophysical plasma systems for which we will never be able to directly obtain the quantitative closure between observations and theory that space-time separated insitu measurements alone can provide.

Measurement Strategy

The measurement strategy has four basic components:

- o Four spacecraft fly in close proximity to form a single probe that can uniquely separate space and time.
- o Use of interspacecraft ranging and communication to explore wide range of scales down to <10 km.
- o Four different orbital phases to cover the entire magnetosphere.
- o Two microsatellites in separate orbits providing stereo connection to global scales.

The spacecraft complement will be launched from a single vehicle. The two imaging spacecraft will be placed in elliptical orbits with apogee of 12 Re and provide continuous imaging of the inner and mid-magnetosphere. The four remaining identical spacecraft will initially be placed in orbits in the equatorial plane. By varying the orbit apogee, the rotation of the line of apsides allows the tetrahedral satellite configuration to pass through many critical boundary regions in the equatorial boundary layers, the dayside magnetopause and the distant tail. The final phase of the mission will involve changing the orbital inclination to polar so that the satellite configuration may pass through the high latitude cusp and magnetosheath boundaries. During all phases of the mission the spacecraft separation will be varied from <10 km to several Earth radii. Such separations will allow space and time variations to be examined for processes operating on micro and mesoscales.

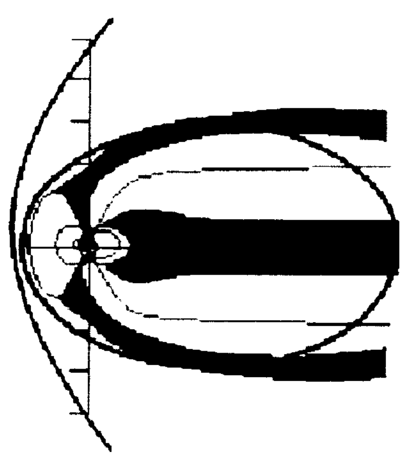


Phases 1-3, Equatorial

The initial orbit is 1.2 x 12 Re (perigee x apogee), equatorial (inclination < 10°), with initial apogee in the nightside. This allows measurements with long dwell times in the near tail region where dynamic changes in the magnetic field occur during substorms and in the dayside magnetopause where reconnection is inferred to occur. Phase 2 extends the apogee of the orbit from 12 Re to 30 Re. Orbit adjustment will be phased so that the apogee remains in the dawnside magnetopause as the magnetic local time of the apogee changes from ~1000 to ~0400. At that time the spacecraft will make one traversal in local time of the midrange magnetotail, dwelling during each orbit near 30 Re. Plasmoid formation, x-line motion, turbulent current disruptions, and plasmoid disconnections are the key processes to study in this distance range. Phase 3 takes the probes past the moon, with midtail apogees - MMS will be able to answer definitively questions about the distant x-line, about plasma entry, and about dynamic plasma tail disconnection and transport characteristics.

Phase 4, Polar

Phase 4 is a 10 x 30 Re polar orbit, with the apogee in the equatorial plane. Although this phase appears superficially similar to the ESA Cluster orbit, this low-eccentricity orbit is the first spacecraft track which can skim the entire dayside magnetopause from cusp to cusp and cover the high latitude transcusp magnetopause. Thus spatial scales and repetition rates of FTEs can be analyzed. This orbit also allows North-South cuts through the magnetotail at 30 Re, complementing the East-West equatorial plane cuts done in Phase 2.



Spacecraft Description

The overall satellite configuration consists of six spacecraft. Four are identically instrumented to perform the measurements outlined in Table 1. They have on-board propulsion for apogee adjustment and inter-spacecraft ranging and alerts to constitute a closely spaced configuration that will enable space and time variations to be separated over scales ranging from a few kilometers to several Re. Sun sensors and a star tracker provide attitude determination. In addition two identically instrumented micro-satellites deployed in separate orbits provide global ENA imaging data. Figure 5 shows the stacked satellite configuration at launch.

Enabling Technologies

There are several new technologies that make the multiscale mission immediately realizable. The sophistication of instrumentation within the small volumes of six spacecraft is due in large part to the dramatic advances made in miniature electronic technology. Not only instrumentation but spacecraft subsystems have benefited from these advances that are being used in almost every aspect of the multiscale mission. Significant advances in miniature radio transmitters and receivers allow interspacecraft ranging to be successfully used for accurate measurements of spacecraft separation distances. Each spacecraft will function autonomously, but the data will form a single boundary layer probe.

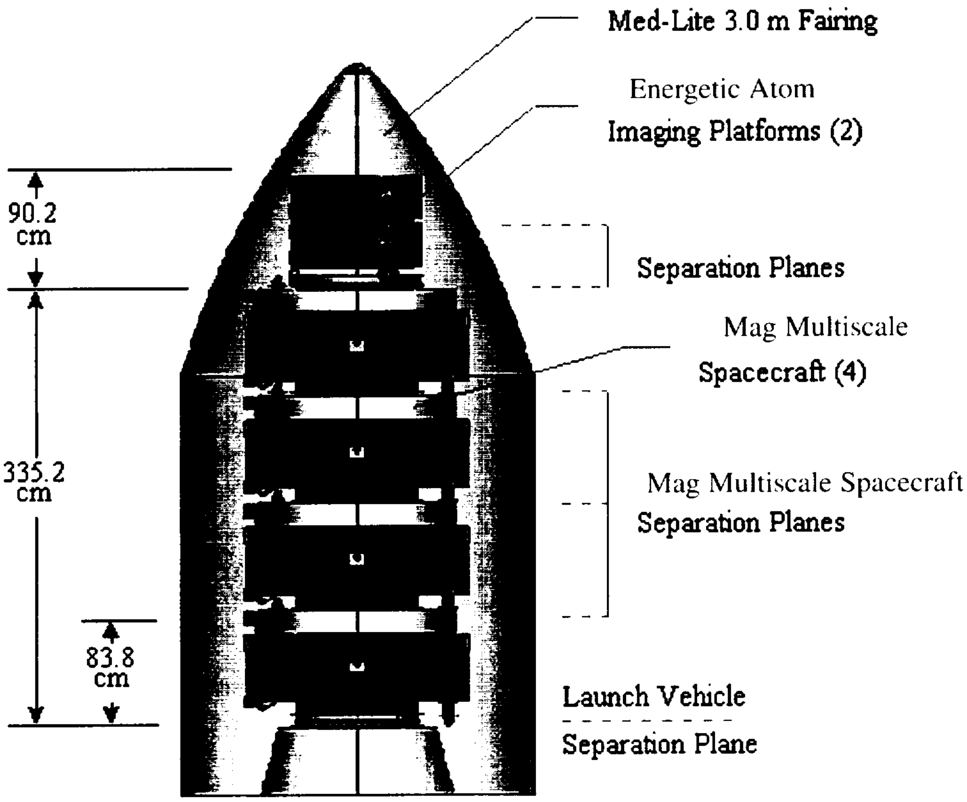
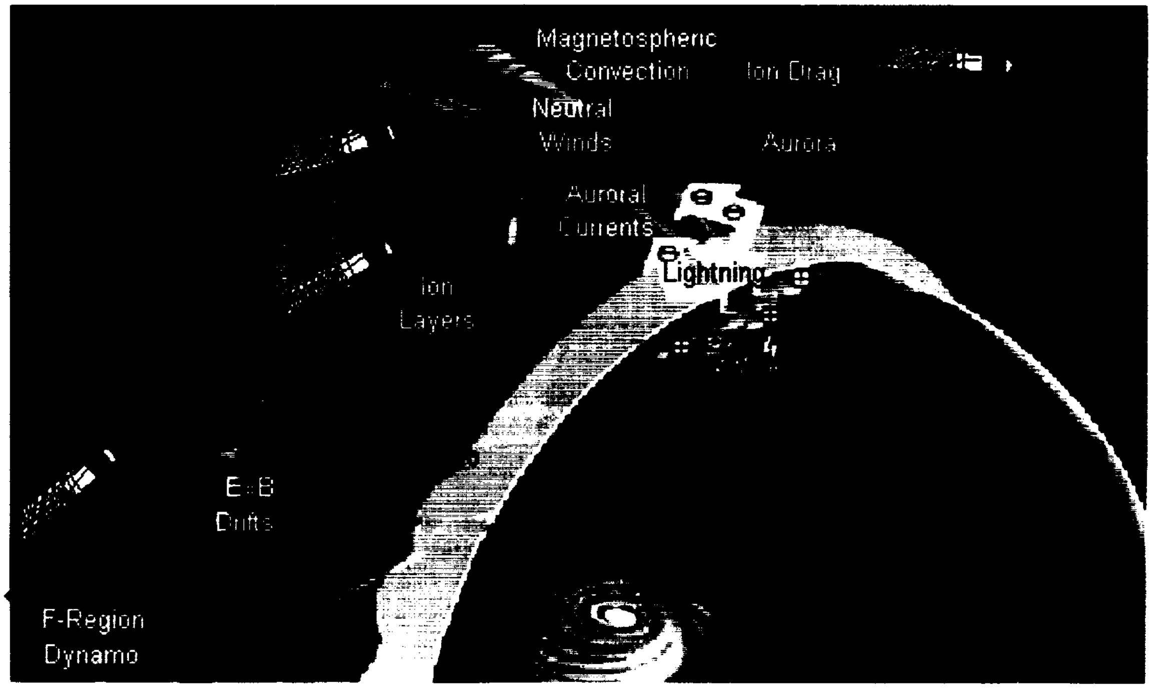


Figure 5. Launch configuration for Magnetospheric Multiscale Spacecraft.

6.2 GLOBAL ELECTRODYNAMICS MISSION

Understanding energy dissipation in the Earth's upper atmosphere over all important spatial and temporal scales.



It should be apparent that a single mission to probe the inner boundary of the geospace environment is not sufficient to resolve all the uncertainties about it's behavior. However, the past and present flight programs undertaken by NASA represent the foundation upon which the next major mission should be based. Following the legacy provided by the TIMED mission to uncover the energy balance of the lower thermosphere and mesosphere it will be necessary to embark upon a mission to elucidate the dynamic response of the region to the energy inputs.

The low-altitude extent of the geospace environment provides a partially ionized collisional plasma that allows electric currents to be generated and dissipated within it. The medium behaves in a nonlinear fashion, since the presence of electric fields in the medium may change the conductivity and currents. Changes in the conductivity at large scales will affect the electrodynamics at smaller scales. Furthermore, the magnitudes of the changes resulting from external inputs will depend upon the present dynamical state of the medium. In order to determine the most important factors determining the dynamics and dynamical response of the lower regions of geospace, it is necessary to make measurements of changes within an already dynamic system. This long-standing problem of space and time ambiguity can only be removed by successive measurements in the same volume of geospace.

The Global Electrodynamics Mission will provide systematic multipoint measurements in the ionosphere-thermosphere system to determine how the ionized and neutral gases exchange energy and how energy is injected and dissipated in the lower thermosphere. Multipoint measurements will enable space/time ambiguities to be resolved and thus enable the distance scales of the most effective energy coupling to be ascertained. Multipoint measurements will provide a means to distinguish between the relative importance of turbulent mixing vs. instabilities in several smaller scale dissipation processes.

Although decades of highly successful experimental programs have recognized that critical energy dissipation mechanisms take place in the Earth's upper atmosphere and often in localized regions, for many of these fundamental processes, we still do not understand HOW these mechanisms actually redistribute and channel energy, and the relative importance of many of the competing mechanisms. This is due to the highly nonlinear nature of many of these processes over a wide range of spatial and temporal scales, the fact that electric fields affect neighboring regions nonlocally, and that the response times for the neutral and ionized gases differ significantly.

The Global Electrodynamics Mission will provide a suite of in situ platforms which will:
1) distinguish spatial and temporal effects; and
2) determine how nonlinear interactions of neutral and plasma gases affect the distributions of each species and thus the electrical coupling that they mediate.

Key Science Questions

- o How are energy and momentum exchanged between ion and neutral gases in the upper atmosphere ?
- o How does the state of the ionosphere determine its response to a given external forcing ?
- o How are the ionosphere and magnetosphere actively coupled ?
- o What are the roles of turbulence and coherent flows in energy exchange processes ?

Required Measurements

Table 2 summarizes the measurement requirements that should be considered.
In order to accomplish the stated objectives, the key characteristics of the charged and neutral gases in the upper atmosphere must be measured. These measurements must be accompanied by knowledge of the magnetic field perturbations and electric fields that are internally generated and imposed from the magnetosphere. Energetic particle precipitation represents a substantial energy source from the magnetosphere that must be quantified at high latitudes. In situ measurements need to be made at altitudes below 200 km and in this region the dynamics of the lower thermosphere and ionosphere are strongly influenced by winds and waves that propagate from lower altitudes. The Global Electrodynamics Mission does not study the global characteristics of the system in any detailed way. Such studies require the simultaneous location of multiprobes at different local times. However, it is important that the ability to describe the large scale characteristics of the system, at least qualitatively, be included in the mission concept. Most conveniently, this can be achieved by remote sensing.

Measurement Strategy

Measurements of the basic state variables describing the ionosphere and thermosphere are required in a region where the interaction

Table 2. Required Measurements for Global Electrodynamics Mission

Parameter	Range	Accuracy
Constituent Atmospheric Density	1-60 amu 10^{6} - 10^{12} cm^{-3}	Δ M/M,1 amu :N,±10 %
Neutral Gas Temperature	100 - 5000 K	±10 %
Neutral Gas Velocity	-3 to + 3 km s^{-1}	±10 m s^{-1}
Constituent Ionospheric Density	1-56 amu 5 - 10^{7} cm^{-3}	Δ M/M,1 amu :N,±10 %
Ion and Electron Temperature	100 to 10000 K	± 10 %
Ion Velocity Vector	0 to 4 km s^{-1}	±10 m s^{-1}
Electric Field Vector	0 to 200 mV m^{-1}	±0.5 mV m^{-1}
Magnetic Field Vector	0 to 60000 nT	±1 nT
Energetic Particle Distribution	0 - 50 KeV	± 1 eV
Auroral Zone Latitude Extent	100-2000 km	±10 km
Neutral Composition below 300 km	1-60 amu 10^{6} - 10^{12} cm^{-3}	Δ M/M,1 amu :N,±10 %

between the ionosphere and thermosphere dominates the energy and momentum balance of the region. In this region below 350 km altitude, the time scales for interactions vary from seconds to a few hours and over spatial scales of a few kilometers to thousands of kilometers. Separation of space and time variations over these scales can only be achieved by ensuring that observations are made sequentially in the same volume. Resolution of time and spatial gradients along the track of the spacecraft require that three satellites be in nominally the same orbit with separation distances varying from a small fraction of an orbit to 1/2 orbit. A measure of spatial gradients across the spacecraft track requires that one spacecraft make similar measurements in the same orbit but displaced in local time.

A requirement to launch all satellites from a single vehicle limits the local time displacement of a fourth vehicle to that achievable from launch maneuvers.

Three spacecraft will be placed into the same elliptical orbit (3000 km x 350 km) and a fourth placed into the same eccentricity orbit at a local time separated from the previous satellites orbit by about 1 hour. The orbit inclination will be 78 degrees, thus allowing access to the highest magnetic latitudes at some longitudes while retaining the ability to access all local times over a relatively short period (3 months).

Each spacecraft will also be equipped with propulsion allowing excursions and retreats to and from perigee altitudes as low as 140 km. Propulsion will also be used to adjust individual orbit periods so that variable spacing along the orbit can be obtained.

Spacecraft Description

The Global Electrodynamics Mission will employ four identically instrumented spacecraft. The requirement for excursions into a high-drag region of the atmosphere is met by providing an elongated geometry along the spacecraft velocity vector, with solar cells deployed edge-on in the wake. Figure 6 shows the configuration of the four spacecraft at launch. A spring-loaded ejection mechanism is employed to deploy the spacecraft that are subsequently three-axis stabilized with the use of Sun sensors and horizon sensors. The spacecraft will be maintained with one axis pointing toward the Earth, thus performing one revolution per orbit. Each spacecraft will carry significant propellant for small adjustments to the orbit period and to support multiple perigee excursions to altitudes of 150 km or lower. It is expected that several hundred excursions will take place during the targeted 2 year mission.

The requirement for remote sensing to provide two-dimensional views of the aurora, such as shown previously in figure 3, and a measure of low-altitude winds, would most sensibly be achieved by incorporating an additional spacecraft in a circular orbit optimized for such measurements. In such a case, careful study is required to ensure that data obtained from perigee excursions, and data obtained from remote sensing is available in the same regions of space at the same time. Specific mission planning will be required to accomplish this task and it should be conducted by a mission definition team that also accounts for the specific capabilities of selected instrumentation.

Enabling Technologies

The Global Electrodynamics Mission addresses the scientific and measurement problems by utilizing four identical spacecraft deployed in two orbital planes with three spacecraft in 1 local time plane and the other displaced by about one hour in local time. The ability to carry four well-instrumented spacecraft into orbit from a single launch vehicle is enabled by the rapid advances in instrument and spacecraft subsystem miniaturization. These spacecraft must include substantial propulsion systems for orbit maintenance and must utilize the highest technology materials development to be accommodated in a single carrier. New instrument devices must withstand high velocity encounters with the neutral atmosphere and ram pressures that, in many cases, will render conventional measurement techniques inoperable. Scientists and engineers have been pursuing these problems for some time and the availability of new technologies has made it possible to overcome the most significant challenges to success.

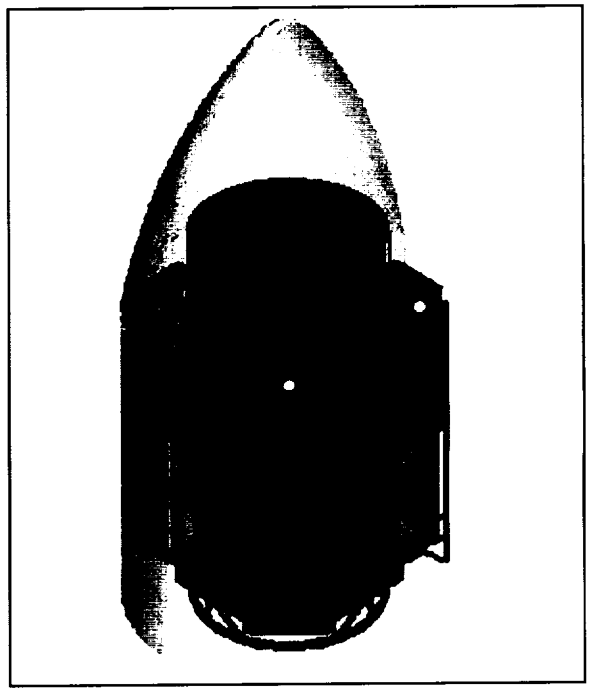
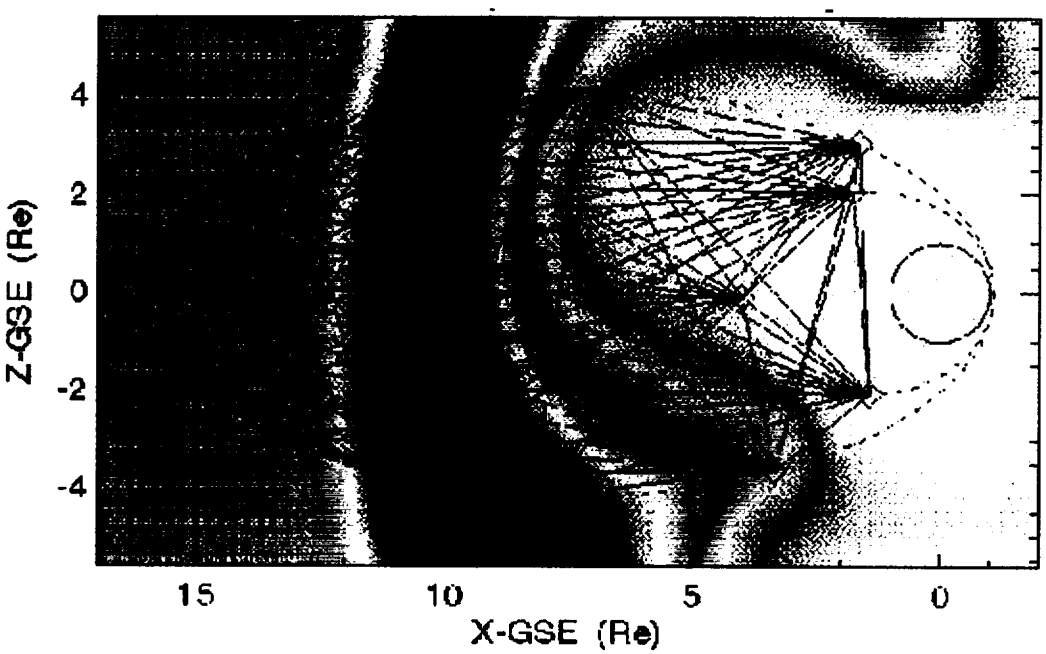


Figure 6. Launch configuration for four principal satellites comprising the Global Electrodynamics Mission and potential fifth spacecraft.

6.3 MAGNETOSPHERIC CONSTELLATION MISSION

Provide instantaneous global maps of plasma and field structures in the magnetosphere.

Radio Tomography and In Situ Sampling



The Earth's magnetosphere is a complex system in which small-scale, localized processes have global consequences. In limited regions we have seen that a snapshot realization of the magnetosphere deviates strongly and importantly from a statistical picture. Yet, to date we have only statistical pictures on which to base our understanding. To advance our understanding of the complex large-scale dynamics of the system, and the global transport within the system, requires at least simultaneous measurements of its interconnected parts at multiple-scale sizes. However, the magnetospheric volume is extremely large and achieving this goal will require the deployment of many observational platforms and the utilization of sophisticated physical assimilation models that will allow the extension of the multipoint measurements into a global image of the magnetosphere. A Magnetospheric Constellation is a very rich mission that will bring several outstanding issues to closure. It is based on two complementary concepts: measure *in situ* and synthesize an image using tomography and assimilative models.

The ISTP mission has determined the connections, quantified the transport, and clarified the issues, but the mechanisms underlying the driving and transport are not known. A Magnetospheric Constellation Mission will reveal how the magnetotail behaves dynamically and could uncover the convection pattern in the magnetotail. The morphology of plasma entry at the dayside reconnection sites will be investigated with sequential passes through them. Further insights into the mechanisms in the magnetosphere that generate aurora will be investigated with the ability to resolve space and time ambiguities. Thus the nature of the feedback of aurora on the magnetosphere can be investigated. Finally the onset and evolution of substorms in the magnetotail can be investigated with suitably located probes that move sequentially through large volumes of space. The magnetosphere is a complex system with several mechanisms operating on many scale sizes. A Magnetospheric Constellation mission will provide the means to uncover how these different mechanisms interact.

Key Science Questions

- o How does solar wind material enter the magnetosphere and where does it go?
- o How does solar wind structure affect the magnetosphere?
- o What is the role of large scale turbulence in the magnetosphere?
- o What are the mechanisms underlying mass and energy flow in the magnetosphere?
- o What causes and what limits energy surges in the geospace environment?

Required Measurements

The most critical questions exposed in the discussions above point to the need for knowledge of the instantaneous configuration of the plasma and the magnetic field in the magnetosphere. The magnetic field configuration cannot be sensed remotely with sufficient accuracy to address the critical questions, and thus the need for in-situ measurements of the magnetic field is paramount. The plasma density and density turbulence may be sensed and imaged remotely by combining radio science techniques with computed tomography. Knowledge of the velocity distribution of the plasma is also required to meet some of the science objectives described above. In situ measurements of the magnetic field and particle energy distribution may be obtained with the use of sensors requiring very limited resources. It is thus sensible to consider these measurements as fundamental to the mission. Beyond these key parameters, added sophistication needs to be considered in relation to the ability to carry the required payload mass to orbit from a single vehicle.

Measurement Strategy

In constructing a measurement strategy for the Magnetospheric Constellation Mission, two important goals must be met. First, multiple in situ measurements are required over substantial spatial and temporal scales in order to separate spatial and temporal ambiguities in the phenomena being observed. Second, a large-scale perspective of the magnetospheric configuration must be continuously observed to determine the feedback between the process occurring within it and its interaction with the interplanetary environment.

The Magnetospheric Constellation Mission strives to combine multipoint, in situ observations with large-scale global images. This very powerful combination of measurement techniques can uniquely advance our understanding of the cross-scale coupling between the global geospace processes and the small-scale kinetic processes. The largest obstacle in achieving this goal is the needed resolution and the vast volume of space. Scale sizes less than 1 Re require >>1000 points to be mapped while in situ observations of only 10 to 100 small satellites are within reach with present technology. The measurement approach of the constellation mission combines the focused sets of in situ observations of 10 to 100 satellites with remote-sensing imaging techniques and sophisticated data assimilation models.

Global Imaging with Radio Tomography.

Global images of plasma density, density turbulence, convection velocity, and magnetic field turbulence, can be provided with radio tomography imaging. Tomographic imaging is a remote-sensing technology which combines very well established radio science techniques with computed tomography (derived from the medical industry). The images require 10 to 20 satellites to form two-dimensional images of slices of the magnetosphere at tens of seconds resolution yielding 100 to 400 pixels. Tomographic imaging is most effective from ~4 Re to ~30 Re above the Earth's surface. This large volume of the magnetosphere can be mapped over an ~ 1-year period. The mission title figure shows the multiple ray paths produced by the radio tomography experiment and the reconstructed density distributions that such an experiment will produce.

In Situ Observations.

Multipoint in situ observation of the magnetic field, plasma flow, energy flow, and currents are critical to the constellation mission. These require electron and ion distributions and the vector magnetic field with about 10-second resolution. The total payload mass is the limiting factor in determining how many spacecraft can be put into orbit. Thus, there is a clear trade-off between the spectrum of observations and the number of satellites. The magnetic field is the most crucial of the measurements, so the most limited spacecraft would have only a magnetometer. The low mass could allow for ~100 such spacecraft. The next level would be to add instrumentation to measure the plasma flow and, at times, the bulk of the energy flow. Electron observations are needed to measure the total energy and energy flow.

Assimilative Models.

The use of assimilative models is essential to the success of the constellation mission. The relatively limited number of probes (20-100) cannot sample the entire volume at the required spatial resolution. Thus, in addition to the radio tomography supplying an image of the magnetospheric density, we will employ assimilative models to complete images of the magnetic field and plasma flows using the point measurements and density images as constraints to the assimilative procedure.

These three measurement strategies are used in complementary ways to address the key science questions. The interspacecraft radiosounding will always provide a picture of the evolving magnetosphere enclosed in the large volume defined by the spacecraft orbits. The spacecraft orbits themselves and the apsidal rotation can allow sequential measurements through key areas of the magnetotail and the magnetopause, thus allowing the space and time evolution of the magnetic field and the plasma flows to be studied during substorms and across plasma entry regions. Finally, at all times the single-point configuration of flows and magnetic field at the satellite locations can provide sensible constraints to MHD models and other assimilative processes that allow a consistent global picture of the magnetosphere to be constructed.

Spacecraft Description

It should be emphasized that the spacecraft are built in a manner that provides a very strong correlation between the spacecraft volume and the spacecraft mass. To the extent that the relationship between mass and volume also exists in the instrumentation, and the necessary support subsystems, then there is a direct relationship between the number of spacecraft that can be accommodated in a single-launch vehicle and the sophistication of the payload. Technology is advancing rapidly in the area of instrument miniaturization and it is thus prudent not to prematurely adopt an absolute approach. Nevertheless, the distinction between a constellation mission that enables radio tomographic imaging of the plasma density in the interior of the magnetosphere and one that does not provides some useful perspectives. A radio tomography mission will allow in situ sampling from 20 spacecraft while simultaneously providing images of the magnetospheric density variations with high temporal resolution. The absence of tomography would allow the number of probes carrying simple magnetometers and plasma analyzers to be increased to 60 or more. Such a configuration would allow a much more detailed description of the magnetic field configuration to be specified in a limited volume of the magnetosphere. It is clear that the configuration of the constellation should depend upon the scientific emphasis of the mission, and that the concept of satellite constellations should be viewed in an evolutionary way.

Two illustrations of spacecraft configurations attached as a stack on a single mother vehicle are shown in Figure 7. On the left, 20 spacecraft, each weighing approximately 20 kg and equipped with onboard propulsion and attitude control is shown. Such a configuration would enable tomographic imaging to be performed in addition to providing the information to study space and time variations at different locations in the magnetosphere. On the right, 60 spacecraft each weighing 8 kg, without onboard propulsion or attitude control, and accommodating basic instrumentation is shown. Such a configuration would provide more in situ data points to constrain assimilative models of the magnetic field and plasma flows, but would not directly diagnose the density distribution within the large magnetospheric volume. A larger number of spacecraft or more sophisticated instrumenta-

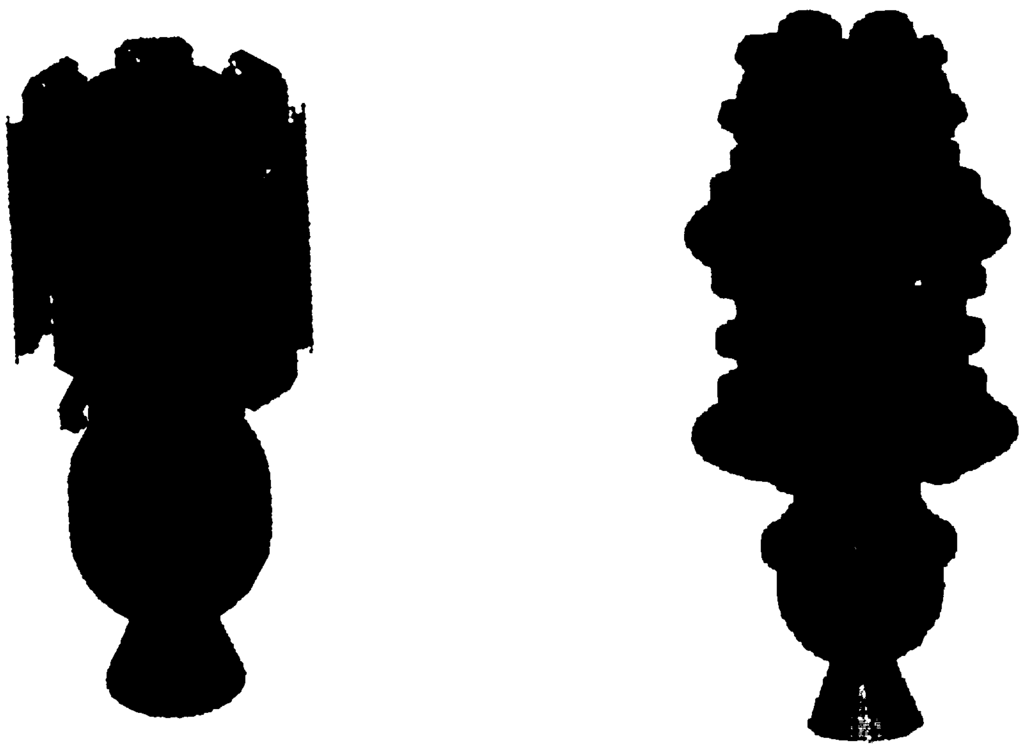


Figure 7. Basic principals employing a mother "tug" vehicle allow the deployment of 20 to 100 spacecraft in specified orbits

tion could be accommodated if technology enhancements allow further component miniaturization. However, science closure with these different emphases can be reached by synthesizing a composite picture of the dynamic magnetosphere at time scales of the order of 3s via simultaneous sampling of particles and fields over spatial scales between 1 and 15 Earth radii.

The constellation spacecraft will be attached to one or two mother vehicles (upper stage) that will be spin-stabilized and have a bipropellant or hydrazine system for ascent to final orbit. One mother vehicle will be used if a single line of apsides and inclination is desired, and will carry a single stack of spacecraft to their final orbits. Two mother vehicles will be used to carry two stacks of spacecraft to their final orbits, if more variable orbital parameters are required for the individual constellation spacecraft. The spacecraft stack(s) will be launched with a single launch vehicle (Med-Lite) to a geosynchronous transfer orbit. The mother vehicle(s) will then raise perigee, and apogee, and reduce their inclination to one or more sets of elliptical orbits. They will release one spacecraft at a time and change their orbit in between releases to accommodate the orbital parameters of each ensuing release. The above scenario allows the realization of a large number of different orbital configurations, subject to a scheme that maximizes science return from a given number of spacecraft and instruments. The present arrangement, that allows science closure within today's budgetary constraints, calls for a release of all spacecraft in a single line of apsides, but with the provision of several satellite groups at different altitudes. This formation is accomplished by placing two spacecraft at higher apogee and separating them by the mean anomaly, while placing two spacecraft at lower perigee and separating them by inclination. The spacecraft can form a tetrahedral configuration approximately 10% of the time. Repetition of the above scheme for different apogee altitudes allows multiple cluster-like configurations to be operational at a given time and covering a large number of sampling points throughout the magnetosphere during any given mission phase. The magnetic field measurements will constrain and validate assimilation procedures to provide global realizations of the current, plasma pressure, density profile, and energy flux density. Multipoint measurements within the volume can also validate the tomographic reconstruction of the electron density in a meridional plane, and thus place those in situ measurements in the context of the global topology.

Enabling Technologies

A magnetospheric constellation mission is enabled by rapid advances in spacecraft construction materials and instrument miniaturization. Modern spacecraft propulsion systems can be utilized efficiently for orbit transfer and adjustments, thus allowing a single launch vehicle to establish an initial orbit for many spacecraft. In summary, placing a large number of spacecraft in their required orbits is a challenge that can be effectively met with present state of the art technology. A significant challenge facing such a mission also lies in the management of the data downlink. But new innovations in this area are likely to be directly applicable to the constellation mission needs. The increasing availability of ground stations may enable conventional data collection activities to proceed at multiple sites. In addition laser communications from the ground are now being seriously evaluated and would allow data transmissions with relatively low power at the spacecraft itself.

SUMMARY

The foregoing science discussions, the required measurements and the detailed implementation plans should provide ample evidence in support of the contention that geospace multiprobes are the next logical step forward in exploration of our environment. The advancement of technology in areas such as mechanical engineering, power systems, circuit miniaturization, high-capacity data storage, and innovative propulsion systems all allow the implementation of multiple satellite configurations within a constrained budget. The problems that have plagued our interpretation of previous data and the advancements that could not be made without the availability of multiple platforms can now be overcome. New multiprobe missions promise to produce a real leap forward in our understanding of the geospace environment for they will allow all the required measurements to be made in all the right places. The most efficient use of resources, and application of experience and knowledge, will be achieved from a series of missions such as envisioned by Solar Terrestrial Probes. The return for our investment in a multiprobe mission sequence is the organized advancement of our understanding in two key areas. First, we will understand the geospace environment to a level that will allow real quantitative assessment of the impacts of humans and the vulnerability of human space systems. Second, this advancement will allow us to more fully evaluate present and future data from other planetary environments to assess differences important to habitability.