

Chapter 5

Report from Magnetospheric Science

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5.1 Introduction and Background

By the early 1990s, magnetospheric physics will have progressed primarily through observations made from Explorer-class spacecraft, sounding rockets, ground-based facilities, and shuttle-based experiments. The field is still dominated by in-situ measurements with remote imaging and active experimentation becoming more prevalent in recent missions. The global geospace science (GGS) element of the ISTP program is the first major new start in the field in over 20 years. Although the spacecraft are still in the class of large Explorers, there are two US spacecraft and instrumentation on a Japanese spacecraft. When combined with contributions to the ESA Cluster mission and vigorous ground-based and computer modeling programs, GGS will form the basis for a major US initiative in magnetospheric physics.

The scientific objectives of the GGS program involve the study of energy transport throughout geospace. The Cluster mission will investigate turbulence and boundary phenomena in geospace, particularly at high latitudes on the dayside and in the region of the neutral sheet at geocentric distances of about 20 earth radii on the night side of the earth.

After ISTP the achievement of further important objectives in the discipline will rely on the development of a three-pronged approach to magnetospheric experimentation combined with a complementary theory and modeling program. The three necessary techniques are: (1) the use of advanced photon and particle imaging of all of the plasma populations of the magnetosphere and the global convection patterns; (2) the use of arrays of spacecraft measuring crucial parameters in carefully selected regions of the magneto-

sphere; and (3) the use of active probing and stimulation of magnetospheric plasmas. The simultaneous use of these three techniques will be needed along with a real-time modeling capability, which is capable of transforming the measurements into a global perspective of magnetospheric processes.

5.2 Current State of Knowledge

The interaction between the solar wind and the magnetosphere is characterized by a continual gradation of disturbance levels that manifest themselves through auroral displays and the intensities of the driving currents of the system. There is some doubt now that there exists a magnetospheric ground state. If there is, it corresponds to conditions of a nearly zero north-south component of the interplanetary magnetic field (IMF).

Increasingly southward components of the IMF lead to substorm activity with extensive auroral displays along an expanded auroral oval. Substorm initiation is associated with a disruption of the magnetotail neutral sheet and a diversion of neutral-sheet current into the ionosphere. The location of the disruption, the role of magnetic reconnection, and the formation of plasmoids that propagate down the tail are topics that are presently under active investigation.

Northward IMF components lead to a strikingly different disturbance state of the magnetosphere. The auroral oval shrinks and moves poleward and the polar cap itself becomes the site of increasing auroral activity in the form of polar cap arcs and, at times, the theta aurora. The field-aligned currents, which drive magnetospheric convection, change their global characteristics substantially, leading to sunward convection in the polar cap. If anything, auroral activity

at dayside high latitudes, near the cusp, becomes more active as nightside auroral activity subsides.

The transfer of solar-wind energy into the magnetosphere for both northward and southward IMF appears to proceed, at least in part, through a process involving magnetic reconnection. For southward IMF, this process results in the formation of flux transfer events, by which solar wind and magnetospheric plasmas intermingle and a convection electric field is imparted to the high-latitude magnetosphere. Flux transfer events appear to form at low latitudes along the dayside magnetopause. Multipoint observations in that region will be required for an improved understanding of this very important magnetospheric phenomenon.

One of the most fundamental problems of magnetospheric physics is the acceleration of auroral particles. It is widely held that electric-field components parallel to the magnetic field are responsible for the downward acceleration of auroral electrons and the simultaneous upward acceleration of ionospheric ions. The parallel E-fields seem to occur preferentially in regions of strong field-aligned currents associated with convective shear reversals in the magnetosphere and ionosphere. Whether the parallel electric fields are localized in altitude as double layers or are greatly extended in altitude is not known. Definitive new information on the auroral potential structure will require the use of multipoint measurements at altitudes of several thousand kilometers above the auroral oval. Active probing of the potential structures with test particles will be necessary for the unambiguous measurement of the parallel E-fields because they tend to occur in regions of strong perpendicular components.

Much has been learned recently about the sources of magnetospheric plasmas. The ionosphere is, of course, the source of thermal plasma throughout the magnetosphere. The ionosphere and the solar wind are both important sources of the more energetic plasma. Recent data has shown that the cusp region is not only the prime site of entry of solar-wind plasma into the magnetosphere but it also is possibly the strongest source of ionospheric plasma to the

magnetospheric regions beyond the plasmasphere. Turbulence in the cusp ionosphere, coupled with strong antisunward convection emanating from the cusp region, leads to the formation of a cusp ion fountain, which feeds accelerated ionospheric plasma to the entire outer nightside magnetosphere. We need to know whether or not this ionospheric plasma is transported to the neutral-sheet region of the magnetotail where it would become an important constituent of the plasma sheet and ultimately the ring current. An answer to this question will require the measurement of thermal plasma composition in the equatorial region of the magnetotail, particularly in the region within about 20 Earth radii down the tail.

Typical magnetospheric plasma distributions contain significant amounts of free energy in the form of beams, loss cones, and other types of velocity-space density gradients. This free energy leads to wave growth and significant wave-particle interactions, which result in the acceleration of electrons and ions and in their precipitation into the atmosphere. Significant new data has been obtained recently on the processes involved in the generation of auroral kilometric radiation (AKR) and auroral hiss as a result of spacecraft that have probed the auroral acceleration regions directly. AKR appears to be generated within plasma density cavities with energy derived from electron loss-cone distributions. A relativistic effect known as the cyclotron maser instability is generally accepted as the generation mechanism. As yet there is no general agreement on the source of auroral hiss emissions except that they also could be generated by electron velocity-space density gradients, possibly associated with the electron "hole" distributions, which are produced by a loss-cone distribution in the presence of a parallel electric field. Other important wave modes, such as ion cyclotron and lower hybrid waves, with frequencies near the ion gyrofrequency have been invoked for the transverse acceleration of ionospheric ions (ion conics) and the parallel acceleration of electrons (suprathermal bursts).

5.3 Science Goals

The ISTP program will include the following major spacecraft missions:

- Wind, a phased mission using double-lunar-swingby and L1 halo orbits to sample the interplanetary medium upstream of the magnetosphere.
- SOHO, a solar observatory at L1;
- Polar, a phased mission using elliptical polar orbits with apogees of 6 and 9 Earth radii. The spacecraft will carry visible and ultraviolet auroral imaging and a comprehensive plasma and fields payload.
- Geotail, a Japanese spacecraft with plasma and fields instrumentation for the in situ sampling of the near and distant geomagnetic tail using double-lunar-swingby orbits extending to distances beyond 200 Earth radii.
- Cluster, four ESA spacecraft in a tight array for study of turbulent phenomena in a 2 by 20 Earth polar orbit with the initial apogee at the equator.

The Soviet Union and possibly other countries will also be contributing spacecraft to the ISTP program.

The overall science objective of the ISTP program is the study of large-scale energy transport in geospace with contributions to smaller-scale turbulent phenomena from Cluster. Aside from the auroral imaging on Polar, all the ISTP spacecraft will use in-situ measurements.

The next significant step in magnetospheric physics beyond ISTP will require the use of global imaging of magnetospheric plasma and energetic particle populations and further use of spacecraft arrays for studies of the spatial structure and temporal evolution of major particle acceleration and energy dissipation processes. The imaging techniques and the use of spacecraft arrays should be employed simultaneously for greater effectiveness.

Because of the lack of global plasma and particle imaging capability on ISTP and the single orbit of Cluster, which will not allow for multi-point measurements near the subsolar magnetopause, in the auroral acceleration regions, or in the neutral sheet within and beyond ~ 20 Earth radii, the following science questions are not expected to be answered satisfactorily by ISTP:

- What processes are responsible for energizing the magnetosphere in the subsolar region of the magnetopause and for phenomena such as flux transfer events, which result from these interactions?
- What is the three-dimensional topology of the magnetosphere and its various plasma boundaries, current systems, and convection patterns, and how do these configurations evolve during magnetospheric substorms?
- What is the three-dimensional structure of the auroral potential structure and how does it evolve in time?
- How is the neutral sheet within and beyond 20 Earth radii disrupted during substorms?

5.4 Magnetospheric Science Missions

Two types of missions to the Earth's magnetosphere will be required after ISTP. The first of these is the global imaging mission, which was advocated in the recently published National Academy of Sciences publication on space science in the twenty-first century. Recently developed approaches to the imaging of plasma populations using photons (e.g., helium 304 Å emissions) and energetic neutral particles (produced in charge-exchange interactions), along with established auroral-imaging techniques, hold the promise of global imaging of the magnetosphere. In addition to auroral imaging from elliptical polar orbits (as with the Polar spacecraft) there is also the possibility of imaging from lunar-based observatories or spacecraft in orbit about the Lagrangian points, particularly L4 and L5. Figure 5-1 illustrates some possible imaging missions.

The second class of missions is the multi-point mission involving arrays of identically instrumented spacecraft with either large or relatively small spacing. An example of a large array would be a set of "current probes" deployed to map the current systems throughout the magnetosphere. Such a network, which was also described in the NASA report on space science in the twenty-first century, would have to be augmented by closely spaced arrays moving through the large-scale network to measure the spatial structure of the electric and magnetic fields,

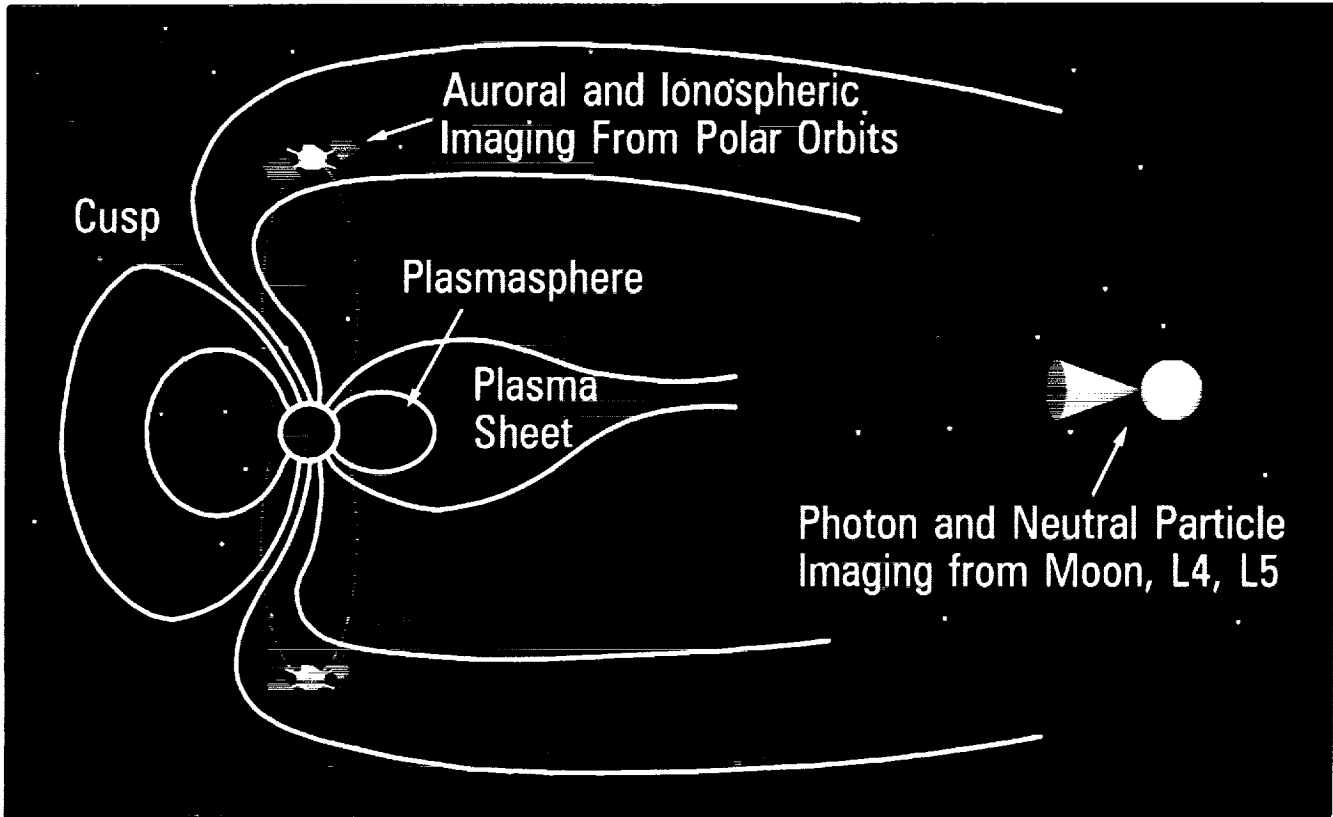


Figure 5-1. Imaging of Auroras, Plasmas, and Energetic Particles

which are the primary observables associated with the current systems.

Indeed, relatively closely spaced arrays (as in Cluster) are needed for the detailed probing of the important plasma phenomena in the magnetosphere. Primary targets for spacecraft arrays with identical plasma and field instrumentation are the low-latitude dayside magnetopause, the auroral acceleration regions at altitudes of 1 to 2 Earth radii along field lines, and the neutral sheet within and beyond 20 Earth radii (the Cluster apogee). Figure 5-2 shows the current probes and various spacecraft arrays in critical regions of the magnetosphere.

Other types of platforms, as well as ground-based observatories, are also applicable to the future magnetospheric science goals. Table 5-1 is a matrix showing the various platforms and the four outstanding science questions from Section 5.3. The double Xs indicate a primary contribution and the single Xs a valuable contribution. The use of manned platforms at low altitudes and inclinations is envisioned as involving active

plasma experimentation as discussed further in Chapter 7 (Space Plasma Science).

5.5 Data Analysis, Modeling, and Theory

Data analysis, modeling, and theory need to be increasingly integrated to make the most effective use of the flight opportunities, to identify unresolved issues and thereby assist in planning future research requirements. On the time scale of the turn of the century, following implementation of ISTP and other programs, we expect to be in a position to attempt a fully quantitative treatment of the phenomena observed in the Earth's magnetosphere.

We assume that by 1995, an internationally based program will have been put in place, with the objective of integrating the scientific output of the US, European, Japanese, and Soviet spacecraft which will explore the different regions of the magnetosphere. In addition to the extended operations and data analysis phases for each of these missions, we recommend a worldwide coordinated effort to combine the global data

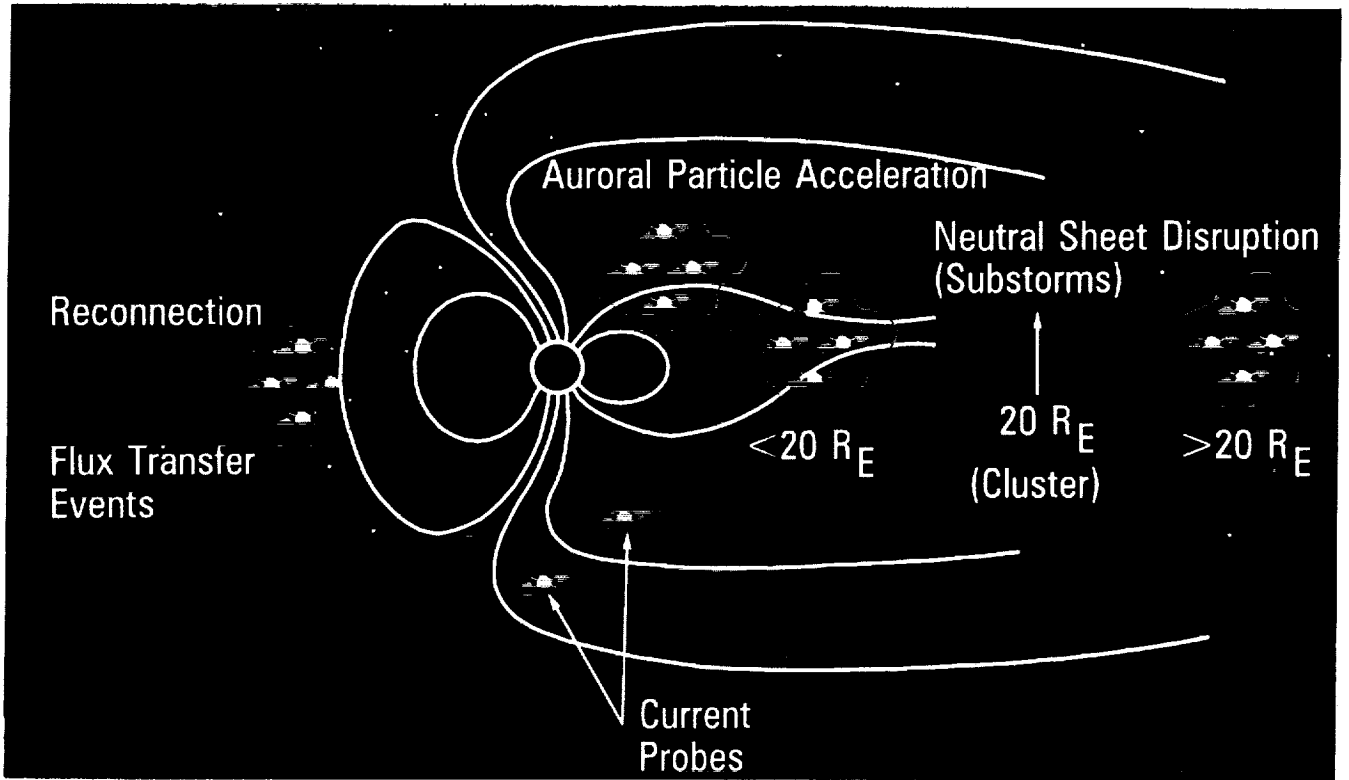


Figure 5-2. Arrays of Spacecraft Needed for Study of Major Acceleration and Energy Dissipation Processes

Table 5-1. Magnetospheric Science Missions

Science Goals				
Platform	Energy Transfer at Subsolar Magnetopause	3D Structure	Neutral Sheet Disruption	Particle Acceleration
Imaging Observatories	X	X		
Multipoint Spacecraft	X X		X X	X X
Manned Station			X X	
Polar Platform		X X		X X
Space Shuttle	\ X		X X	
Sounding Rockets			X X	
Ground Based		X X		

XX denotes primary mission, X denotes secondary mission
 Imaging observatory would view HeII 304 Å and energetic neutral atoms
 Chemical releases in crucial regions could enhance imaging
 Injection of test particles is needed for probing of acceleration regions
 Continuous monitoring of the interplanetary environment is needed for all missions

sets and carry out the scientific analysis of the data across all the missions. This requires a new initiative, a new way to organize and manage the scientific optimization of multi-spacecraft international flight programs. One approach would be to have an official data analysis mission, which would utilize essentially the same management and methodologies as a flight program.

The knowledge thus acquired would be unprecedented in quality and quantity, and would provide the basis for:

- A truly quantitative three-dimensional modeling capability
- The full-scale merger of data analysis and theory systems.

Parallel theory and modeling efforts, in close cooperation with the development of data analysis techniques, should lead to:

- Development of a magnetospheric global circulation model
- Simulation of physical processes at all scales
- Use of local, high-resolution particle-code simulations to analyze and interpret data from clusters of spacecraft
- Ability to “fly” spacecraft through MHD (magnetohydrodynamic) and single-particle computer models and generate a simulated data set.

5.6 Advanced Instrument Development Program

The lead times and hence the costs of future magnetospheric missions could be measurably decreased through an advanced instrument and spacecraft development program. An effective program would include the following elements:

- Fund as an identified line item in NASA budget to stress its fundamental importance.
- Develop instruments to engineering model level. Define refined costs through this

approach with the goal of lowering cost and shortening delivery time.

- Fund competitive studies of standardized low, medium, and complex spacecraft. Implement one of each based on competitive selection to establish accurate cost and interface models.
- Fund parallel systems research (to above items) of present system of implementing missions. The synergistic goal would be to reduce costs by identifying cost/benefit payoff of present methodologies with elimination of non-beneficial elements.
- Base selections on relevance to mission plans through 2015.
- Specific recommendations would be to (1) emphasize remote sensing of magnetosphere for global physics, and (2) develop low cost, standard cluster spacecraft to examine relevant microphysics.
- Correlate with theory and modeling programs to establish key regions and parameters to be targeted for verification and refinement of models and theory.

5.7 Crucial Elements of the Future Magnetospheric Physics Program

Accomplishment of the science goals of the future in magnetospheric physics will require the development of several crucial programs and capabilities, including:

- Photon and/or neutral particle imaging of the aurora and of all the plasma populations of the magnetosphere
- Arrays of low-cost spacecraft measuring critical parameters in carefully selected regions
- Active probing and stimulation of magnetospheric plasmas
- A vigorous theory and modeling program
- Missions to data bases
- An advanced instrument and spacecraft development program
- Continuous solar-wind monitoring.