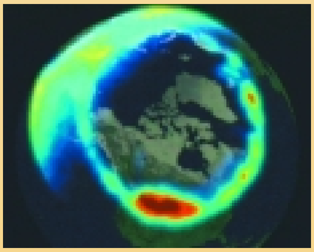

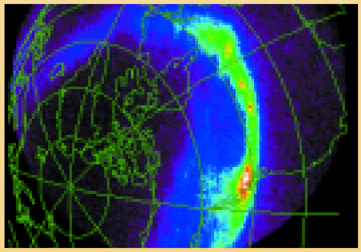

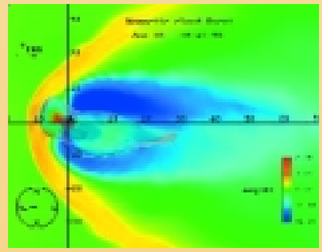

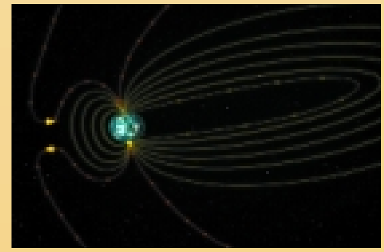

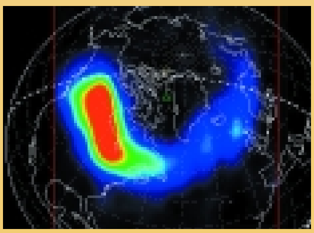

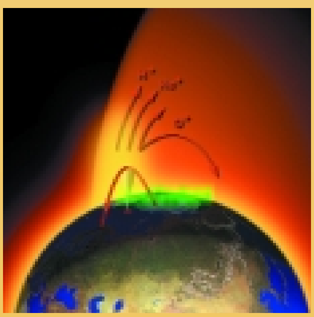

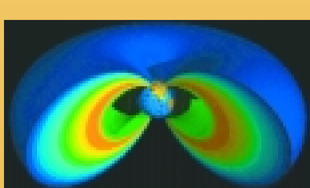

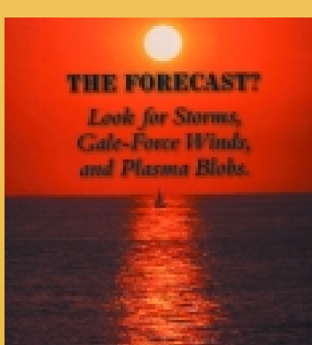

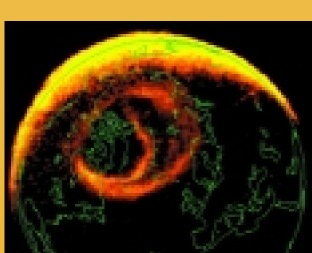

May 14, 2001

ISTP/GGS

Global Geospace Science for the International Solar-Terrestrial Physics Program

National Aeronautics and Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

ISTP/GGS

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for the International Solar-Terrestrial Physics Program

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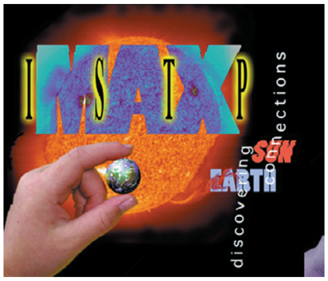
Please note:
Because ISTP/GGS consists of three spacecraft missions, coordinating ground observing campaigns, and a theory and model program, OSS has allowed an exception to the Senior Review proposal page limit. This proposal is 1.5 times longer than standard.

I. Executive Summary



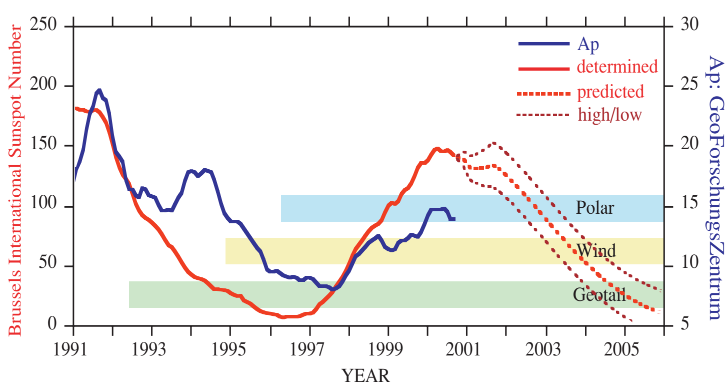
ISTP constitutes NASA's Flagship Mission to study the Sun and its powerful influence on the Earth. The present proposal discusses the GGS portion of ISTP— a distributed spacecraft observatory (Wind, Polar, Geotail) in strategically-placed orbits, carrying 25 scientific instruments, a ground-based set of observatories, and an extensive theory and modeling effort. The ISTP/SOHO Mission is addressed in a separate proposal. In addition to its scientific investigations, GGS includes an entirely open data system of benefit to the wider scientific community and an active education and outreach effort. ISTP/GGS has amply demonstrated its unique ability to take a coordinated systems approach to the tightly-coupled, highly time-dependent system that we call "the Sun-Earth connection."

Accomplishments: ISTP has shown that it is practical to follow solar eruptive events from near their site of origin, track them through the interplanetary medium, measure their properties near Earth, and finally quantify the way in which the energy is coupled to and dissipated in the magnetosphere and ionosphere. The knowledge gained has been used to produce predictive global models that organize the varied phenomena in a cohesive way. Our principal accomplishments underscore the value of a systems approach to Sun-Earth connections. Examples include:

- The importance of colliding CMEs, especially their effect on shock front propagation, has been uncovered for the first time.
- Evidence has been found that collisionless reconnection is the most important energy transfer process between the solar wind and the magnetosphere, and is more widespread than first realized, including on the flanks of the magnetopause, poleward of the cusp, in the deep tail, in the near-tail, and even in the solar wind.
- The near-Earth neutral line has been identified to lie within 20 to 30 R_E down tail, but auroral brightenings have been traced to closer distances, re-raising the issue of the cause of substorm onset.
- Our perceptions of the solar wind and of terrestrial plasma sources have changed dramatically, raising the question of their relative roles in magnetospheric dynamics.
- The value of data based physical modeling of the global transport of particles from all sources and energies throughout the magnetosphere has been proven, based on the realization that a synergisitc interaction is required between the end-to-end observations of a variety of events and the simulations of the system response.

New Perspectives: The future of ISTP/GGS is to pursue the new science questions that have come about because of these and other discoveries. We plan in the next several years to fully exploit the flexibility of Wind, Polar, and Geotail to gain a fresh and unique perspective on the Sun-Earth connection problem. Wind has already been placed in an orbit that will take the spacecraft to distances up to 400 R_E from Earth in the direction normal to the Earth-Sun line. Beginning in 2004, Wind will sample the distant magnetotail, its boundaries, and its interaction with the solar wind. From the vantage point of these new orbits, Wind will investigate, with ACE and Geotail, the 3-D geometry of large-scale interplanetary structures such as magnetic clouds, CME shocks, and distant parts of the bow shock. The resultant models of important, geoeffective solar wind structures will be used to provide more reliable boundary conditions to modeling codes that predict geospace response. The theoretical modeling codes have reached a new maturity that will help validate our understanding of fundamental processes and enable more definitive comparisons between observational inputs and global simulations.

The Polar orbit apogee has evolved equatorward allowing it to investigate substorm ignition processes during particle injection events near L=4 to 9 R_E. Magnetopause skimming orbits with Cluster in the cusp will allow a variety of detailed, quantitative analyses of reconnection. Polar now enters a new phase of studies of the ring current and the relativistic electron belts. The Geotail orbits will be used with Polar near the equator to investigate the true nature and mechanism of substorm onset and development.



Prediction values are based on ISES cycle 23 forecast

Figure 1. Past and predicted solar cycle (red) along with history of activity index Ap (blue). The proposed extended mission will cover the end of the current solar maximum and the declining phase of the solar cycle.

New Science Objectives: The current proposal spans solar maximum, characterized by powerful transient events and coronal mass ejections, and the approach to solar minimum, characterized by large transient equatorial holes. These latter structures are associated with long-lived, high velocity solar wind streams that produce recurrent geomagnetic storms and which somehow produce the largest fluxes of damaging MEV radiation belt electrons. We propose to take full advantage of ISTP assets to accomplish the following general goals for the extended phase:

1) **We will extend the system science approach describing the dynamic processes associated with the decline of the solar cycle.**
2) **We will understand the dynamic processes associated with the equatorial region of 2-30 R_E.**
3) **We will establish which are the controlling reconnection processes and quantify their relative importance for system dynamics.**
4) **We will quantify the influence that terrestrial source plasmas have on magnetosphere dynamics.**
5) **We will quantify the 3-D structure and evolution of large-scale interplanetary configurations and their interaction with the magnetosphere.**

Data Accessibility and Societal Impact: In addition to those directly involved with the program, the wider scientific community benefits from the ISTP/GGS open data system. The extensive, easily accessible, and rapidly available ISTP/GGS database encourages the prompt investigation of many solar-terrestrial events of special interest and, by about 2005, will allow comparison and analysis of measurements over almost an entire solar cycle. Furthermore, the library of magnetospheric simulations and terrestrial auroral images has been used extensively in our education and outreach efforts to inform teachers, students, and the public at large, of the importance of Sun-Earth connections. The ISTP outreach program has been eminently successful in making the public aware of Sun-Earth connections and we will continue our commitment in this important area.

The ISTP/GGS assets are fundamental elements of the global approach to understanding Sun-Earth connections as a system. The next several years will put that approach to the test with extreme events expected during the declining phase of the solar cycle. This proposal reflects our intent to use the healhy assets of ISTP and of the many collaborating missions to continue to build our understanding of the physics of the Sun-Earth system as a whole during a full solar cycle.

II. ISTP/GGS- The Right Thing In the Right Place at the Right Time

A. Overview

The Global Geospace Science (GGS) program consists of three spacecraft missions, coordinated ground observing investigations, and theory and modeling investigations. The missions are: Wind, a fully instrumented solar wind observing platform [*Russell*, 1995]; Polar, a particles, fields and imaging spacecraft for the polar and inner magnetosphere [*Russell*, 1995]; and Geotail, a particle and fields spacecraft targeted at magnetotail dynamics [*Terasawa and Kamide*, 1994]. Geotail is a joint effort with the Japanese Institute of Space and Astronautical Science (ISAS). Spacecraft observing campaigns are regularly coordinated with the ground segment, SuperDARN, CANOPUS, Sondrestrom and SESAME. The GGS theory and modeling component supports the development and utilization of physics-based geospace models, which include, and are verified against, GGS observations. This proposal describes the accomplishments and future science goals for these five elements.

GGS together with SOHO and Cluster (covered by separate proposals) constitute the larger International Solar Terrestrial Physics (ISTP) program. The original paradigm of ISTP was to acquire simultaneous data from five critical locations in the Sun-Earth connection system, the Sun, the heliosphere, and the magnetosphere's polar, equatorial and tail regions. ISTP would then utilize data driven, physics-based, global dynamic models to integrate the data into coherent dynamic descriptions of geospace. Four ISTP spacecraft were launched to accomplish the objectives of the program, two into the solar wind (SOHO from ESA [*Fleck et al.*, 1995] and Wind from NASA) and two within the magnetosphere (Geotail from ISAS and Polar from NASA). In addition, ISTP has benefited greatly from expanded coverage of the key regions afforded by the launches of SAMPEX, Interball, FAST, ACE, and IMAGE.

The ISTP/GGS mission is unique in that it operates as a distributed laboratory. Transient events are routinely followed from their birth on the Sun, traced through the interplanetary medium, characterized as they near Earth, and quantified in terms of their geoeffectiveness in creating magnetic storms, accelerating magnetospheric plasma and depositing energy into the atmosphere. GGS examines the variability of the geospace environment and its underlying dynamics on large and small time and spatial scales, comparing the geospace response to solar events during both quiescent and dynamic periods. As such, ISTP/GGS has grown to be a flagship for future, larger efforts to understand the solar-geospace system.

Table 1. ISTP Elements

ISTP/GGS	Other ISTP	Collaborating Missions
Wind	SOHO	FAST
Polar	Cluster	SAMPEX
Geotail		Interball
		IMAGE
Ground-Based Investigations		ACE
Theory & Modeling		Ulysses

Elements of ISTP, ISTP/GGS, and the collaborative mission. This proposal covers the five elements of ISTP/GGS.

The ISTP/GGS Science Program

When ISTP/GGS was formulated following the scientific achievements of ISEE and Dynamics Explorer, the space physics community was quite sure what it was looking for and where it should be located. After all, two decades of exploration had defined the landscape quite well and well-developed theories had predicted what remained as uncertain terrain.

With this vision in mind, Geotail went far down the magnetotail to look for fireballs, plasmoids and substorm onset instabilities. Wind was to be placed as close as possible to L1 to monitor the solar wind and Polar was boosted high over the northern polar cap to image the aurora and look for the origins of plasmas in the Earth's neighborhood.

Fortunately, the ISTP/GGS missions were built for flexibility. When Geotail didn't find the source of substorm dynamics at 200 R_E, we had to wait for the Geotail apogee to be reduced to 50 R_E and then to 30 R_E where the near-Earth neutal line discoveries were made. Wind was flown with ample fuel reserves allowing it to enter the double lunar swingby orbits to monitor the solar wind closer to Earth and along the entire path to L1. Polar was outfitted with the most complete array of imaging, fields and particles instrumentation ever flown which meant assumptions regarding what should be seen did not cloud understanding of what was seen.

Six discoveries significantly changed the future of Sun-Earth Connection physics:

1) The discovery that the deep magnetotail does not hold the key to magnetosphere dynamics. The "action" is much closer to Earth and there is still work to be done to determine exactly where and how the action starts.
2) The discovery that collisionless reconnection is "the" most important energy transfer process between the solar wind and magnetosphere and this process may be much more important and widespread than first appreciated.
3) The discovery that the terrestrial source of plasma can mass load the outer magnetosphere system very quickly after solar impulsive events and thereby may be a catalyst or even a driver, rather than a consequence, of magnetospheric dynamics
4) The discovery that shock fronts in the solar wind can be so steeply inclined that they reach Earth before they are observed at L1. Therefore, propagation of solar wind structures from L1 to the magnetopause, essential for reliable modeling of the geospace response, but fraught with uncertainties.
5) The recognition that the different phases of a single solar cycle produce very different solar wind input conditions to the magnetosphere and that the magnetosphere in turn responds very differently to these differing inputs.
6) The determination that the coordination of single point satellite measurements with global physics-based geospace models can produce reliable dynamic images of geospace.

Our principal accomplishments underscore the value of a systems approach to Sun-Earth connections.

Goals for the extended phase

The future of ISTP/GGS is the pursuit of new science questions that have come about because of these discoveries. Careful focusing of the efforts is proposed to achieve closure on goals of immediate importance for the advancement of space physics research. We feel it is important to study the main problems, the main areas of current uncertainty.

1. **We will extend the systems-science approach, describing the dynamic processes associated with the decline of the solar cycle.** This will be based on observable quantities and be demonstrable through realistic physical 3D global models of the magnetosphere system.
2. **We will understand the dynamic processes associated with the equatorial region of 2-30 R_E.** We will quantify the relative influences that solar and terrestrial source plasmas have on dynamic equatorial processes. We will determine the equatorial storm plasma injection and loss as a function of solar input. And, we will understand the connection between radiation belt time variations and their direct connection with solar variability.
3. **We will investigate the global consequences of magnetic reconnection.** We expect to gain an understanding of substorm onset and instability processes associated with the inner magnetosphere. We will establish which are the controlling reconnection processes and quantify their relative importance for system dynamics. Merging versus current disruption? Component versus antiparallel merging? Which are controllers, which act as regulators? Are the fundamental processes different on the dayside, the flanks and in the tail?
4. **We will quantify the 3-D structure and evolution of large-scale interplanetary configurations and their interaction with the magnetosphere.** The evolution and dynamics of large scale interplanetary structures such as corotating interaction regions (CIRs), magnetic clouds, shocks, flux ropes, etc. will be characterized using the new 3-point heliosphere configurations.

The New Strategy for Orbits in ISTP/GGS

These goals are possible for three reasons: 1) the GGS spacecraft are healthy. Foldout 2, located in Section VII, contains payload information including the capability and operational status of each instrument. 2) The original GGS spacecraft have been joined by the last element of ISTP, Cluster, and other SEC-related missions, including SAMPEX, FAST, ACE, IMAGE and Interball. 3) The GGS spacecraft orbits have been strategically altered or have precessed into ideal positions from which to study the critical dynamic processes associated with the declining phase of the solar cycle. Foldout 1 displays the complete set of old and new orbit configurations and summarizes the science results to be expected from each, both singly and in conjunction with other spacecraft.

Wind: Wind was launched on November 1, 1994 into a double-lunar swingby orbit with an apogee of 250 R_E. See Table 2 (and Foldout 2) for a description of the six field and particle instruments and two gamma-ray instruments onboard. As the Interplanetary Physics Laboratory, Wind defines the state of the solar wind upstream of Earth through key measurements of solar wind plasma, solar energetic particles, and the interplanetary magnetic field. In addition, Wind makes remote observations of terrestrial and solar radio waves, including the radio emission associated with CME shocks. With its large fuel reserve, the spacecraft has enjoyed enormous maneuvering flexibility: Wind has explored new regions of space both inside and outside the magnetosphere, and in the next several years will explore the heliosphere and deep tail in two novel orbital configurations at distances from Earth of up to 400 R_E. Remote tracking of CME shocks from the outer corona to Earth with 2-D direction finding is possible and is a unique capability of Wind.

Until late 2003 or early 2004, Wind will be in a Distant Prograde Orbit (DPO) that takes the spacecraft to distances of up to 360 R_E ahead and behind Earth in its orbit (see Foldout 2, Figure C). The DPO forms, with ACE/SOHO and Earth-orbiting spacecraft, a large baseline perpendicular to the Earth-Sun line. No spacecraft has explored this region of space until now. The interplanetary measurements made possible by this unique configuration will provide for the investigation of large-scale interplanetary solar wind structures and provide precursor observations beneficial to the in situ plasma experiments on the upcoming Stereo mission.

Beginning in early 2004, Wind will transition into a series of large, kidney-shaped Earth Return Orbits (ERO) having a 400 R_E apogee (see Foldout 2, Figure D). In the ERO, Wind will investigate the deep (about 320 R_E downstream) magnetotail, and explore dayside regions complementary with ACE and SOHO near L1. Between the DPO and ERO, Wind will execute a number of near-Earth phasing (petal) orbits which are useful for near-Earth solar wind and inner-magnetospheric studies.

These distant orbits are made possible by the increased communications margin provided by the Wind Transmitter-2 and the ample fuel reserves. The positioning of ACE at L1 provides solar wind monitoring freeing Wind to explore more distant regions in preparation for the Stereo mission. Sufficient fuel reserves will remain after the proposed maneuvers to place Wind near the L1 point if ever the need occurs.

Table 2. Wind

INSTRUMENT	CAPABILITY
MFI	DC — 10Hz vector magnetic field
SWE	3D electron velocity distributions: 7 eV — 22 keV 3D ion velocity distributions: 200 eV — 8 keV
3DP	3D electron and ion distributions: eV — MeV
SMS	Energy, mass, charge composition solar wind ions: 0.5-230 keV/e
EPACT	Energy spectra electrons and ions: 0.1 — 500 MeV/nucleon Isotopic composition, Angular distributions
WAVES	Radio and plasma waves: dC — 14 MHz
TGRS	Gamma ray spectroscopy: 15 keV — 10 MeV
KONUS	Gamma Ray spectroscopy: 10 — 770 keV, high time resolution

Fully Operational | Non-impacting fault | Operates under special circumstances | Non-Operational

Polar: The Polar satellite, launched on February 24, 1996, is in a highly elliptical orbit with a period of about 17 hours. The inclination is 86˚, apogee is at 9 R_E, perigee is at 1.8 R_E geocentric, and the line of apsides precession rate is 17˚ per year. Within the ISTP fleet, Polar has the responsibility for multi-wavelength imaging of the aurora, measuring the entry of plasma into the polar magnetosphere and the geomagnetic tail, the flow of plasma to and from the ionosphere, and the deposition of particle energy in the ionosphere and upper atmosphere [*Hoffman et al.*, 1996]. Polar was launched to cover the polar magnetosphere and, as its orbit precessed with time, can now cover the equatorial inner magnetosphere.

Over the next years, the Polar apogee will pass through midnight local times at near equatorial latitudes in the fall of each year and noontime equatorial latitudes each spring (see Foldout 2, Figure F). As the orbit evolves, so do the opportunities to acquire data appropriate for new science questions. The traversals of the radiation belts and the heart of the ring current continuously improve as apogee moves through mid-latitudes. A well-instrumented spacecraft scanning in the crucial L=4 to 9 R_E nightside transition region, where the field changes from dipolar to tail-like and plasma pressure gradients are largest, is just what has been needed to observe energetic particle injections and map the terrestrial plasma source profile. Polar has now assumed part of the role of the original “Equator” spacecraft envisaged for the “OPEN” program.

Polar carries 11 science instruments plus an engineering experiment (see Table 3 and Foldout 2). Three imagers provide tri-spectral imaging in ultraviolet, visible and x-ray wavelengths; these are mounted on a despun platform to optimize viewing of the aurora and other targets. Polar carries five types of charged particle detectors to sample electron and ion populations and perform mass identification, from thermal to relativistic energies. Polar’s electric and magnetic field instruments include dual high resolution fluxgate magnetometers, and the first successful triaxial electric field instrument with ultra-high time resolution burst-mode capability. A special loss cone charged particle imager on the despun platform complements the body-mounted charged particle experiments. The TIMAS mid-energy particle detector was recently restored to full operation after the spacecraft was commanded to its redundant telemetry service module.

Table 3. Polar

INSTRUMENT	CAPABILITY
MFE	DC — 10Hz vector magnetic field
EFI	3D electric field Thermal electron density
PWI	Spectral and wave vector characteristics: 0.1 Hz to 800 kHz
CAMMICE	Energetic particle composition: 6 keV/Q to 60 MeV per ion
CEPPAD	Protons: 10 keV to 1 MeV; electrons: 25 to 400 keV
HYDRA	3D electron distributions: 3D ion distributions: 2 — 35 keV/e
TIMAS	3D mass separated ions: l5eV/e to 32 keV/e
TIDE	2D ions: 0 to 500 eV/e
UVI	Far ultraviolet auoral imager: 130.4, 135.6, 140-160, r160-175, 175-190 nm
PIXIE	X-ray auroral imager: 3 to 60 keV
VIS	3 low-light level auroral cameras: 130.4, 391.4, 557.7, 630.0, 656.3, 732.0 nm

Fully Operational — Non-impacting fault — Operates under special circumstances — Non-Operational

Polar Operations After Completion of Semiannual Pointing Maneuvers

On-board fuel reserves are sufficient to continue the present mode of operations well into 2003, at which time the spin axis will be reoriented normal to the ecliptic plane. **The new orientation will have no effect on our ability to address the science objectives proposed for the continuing mission.** All instrumentation will remain functional in this new orientation. The primary field and particle instruments are 3D and will continue to provide full spatial coverage. The despun platform imagers will provide significant auroral coverage of about 6.5 hours during each 18-hour orbit. The anticipated simultaneous imaging of aurora in both hemispheres is shown in Figure 2. Actual images acquired during the equatorial mission phase will be used to investigate the important issue as to whether the auroras are actually conjugate or significantly differ because of the mechanisms for the precipitation of auroral particles into the atmosphere. An advantage is that the standard issues of timing, intercalibration and wavelength, normally problems for the intercomparison of data from two sources, are eliminated [*c.f. Craven et al.*, 1991].

During the fall of 2003, the apogee of IMAGE will also be in the equatorial plane. Auroral observations from both Polar and IMAGE will be needed to obtain maximum coverage. An example of this complementary coverage occurred during the extensively studied Bastille Day event of 2000. It is this combination of data from the Polar and IMAGE cameras that provided complete coverage of the important auroral activities that day.

We believe Polar provides invaluable and irreplaceable science support for ongoing and future missions. The current IMAGE mission and the planned TWINS mission have assumed there will be in situ measurements of the inner magnetosphere to support their remote sensing and global ENA imaging observations. When performing the analysis of specific events, static inner magnetosphere models cannot provide the proper information for inverting the ENA and optical images and the conversion to estimates of the global magnetosphere content, composition, energy and energy flow. These imagers view an “optically thin” medium

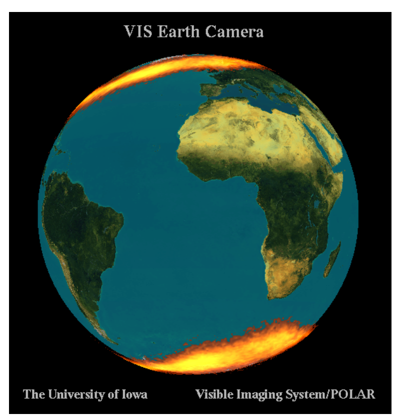


Figure 2. Simulated auroral imaging capabilities of the VIS Earth Camera with Polar apogee near the equator. The field-of-view is sufficiently large to simultaneously image both Northern and Southern hemispheres. The great promise of such imaging is shown in this example for which the actual Northern aurora has been mapped into the Southern hemisphere assuming magnetic conjugacy.

through a single line of sight per pixel. Converting those data to fluxes, energy densities, and spatial distributions is not yet reliable without a realistic picture of some part of the actual system, its spatial structure and how it is varying. Polar observations along a path through the images establish the baseline for image inversion. Although TWINS will provide "stereoscopic" ENA views of the inner regions, the analysis will still require "ground truth" measurements from Polar to confirm reliability.

Geotail: The joint Japan/US Geotail satellite inaugurated the ISTP Program with its launch on July 24, 1992. Geotail carries two US experiments and five Japanese experiments, three of which have US co-investigators (see Table 4 and Foldout 2). The Geotail instrumentation provides excellent measurements of plasmas, energetic particles, electric and magnetic fields and plasma waves. During the initial phase of 28 months, Geotail carried out the most comprehensive survey ever made of the distant magnetotail out to distances of 200 R_E from Earth. After these first 2 years in the deep magnetotail, the apogee of the Geotail spacecraft was first reduced to 50 R_E in late 1994 and then to 30 R_E in early 1995. These reductions in apogee position provided surveys in the cislunar position and then near the predicted near-Earth neutral line at radial distances of 20 to 30 R_E. The current orbital position with perigee at 10 R_E and apogee at 30 is ideal for studies of several important regions of the magnetosphere, including the dayside magnetopause, the boundary layers along the flanks of the magnetosphere, the dynamic behavior of the plasma sheet at 20 to 30 R_E, and its relationship with the outer edge of the extraterrestrial ring current at 10 R_E. The fact that the orbit inclination is near-equatorial is a major advantage since the dwell time in the plasma sheet is maximized, for example. The changes in the perigee and apogee positions each year are minor, and the apogee position shifts by about 15 degrees per year in inertial coordinates. Thus, during the course of a year, radial distances in the range of 10 to 30 R_E are sampled at daytime local times and also in the nighttime plasma sheet. Since the failure of the IMP-8 magnetometer, Geotail and Cluster have become important near-Earth monitors. Their apogees reach the dayside solar input regions at opposite seasons such that the combination provides quasi-continuous coverage of extreme solar wind conditions as they approach the magnetopause.

Table 4. Geotail

INSTRUMENT	CAPABILITY
MGF	Dc — 8 Hz vector magnetic field
EFD	Double Probe Electric Field
PWI	Electric (0.5 Hz —400 kHz) and Magnetic (1 Hz —10 kHz field waves
HEP	Energetic and High Energy Cosmic Ray particles
EPIC	Energetic Particles and Composition 10 -230 keV
LEP	3D velocity distributions 7eV-42 keV ions, 6 eV-36 keV electrons
CPI	3D velocity distributions 1eV-50 keV ions and electrons

Fully Operational — Non-impacting fault — Non-Operational — Operates under special circumstances

Theory and Modeling Investigations

The integration of theory and modeling with spacecraft and ground-based observations is an integral part of ISTP/GGS. The mission-oriented models developed as part of this program are designed to provide the global context for the ISTP/GGS spacecraft and ground-based measurements. Global dynamic simulations are used, with coupled micro and mesoscale simulations where appropriate. At the global level are 3-D magnetohydrodynamic (MHD) codes that simulate the interaction of the impinging solar wind on the magnetosphere, and its coupling to the ionosphere. The ionospheric response enters as a coupled electrostatic 2-D submodel that serves as the inner boundary to the MHD code.

Computational submodels have also been developed to couple a global MHD code to a relativistic guiding center test particle code to model the dynamic response of the radiation belt particles to variability in the upstream conditions. A global MHD code has also been coupled to test particle codes in the large-scale kinetics approach that reconstructs distribution functions for comparison with satellite measurements. Finally, a submodel based on nonlinear dynamics techniques has been developed to accept input from Wind or other upstream spacecraft and predict the expected values for several commonly used magnetospheric indices.

Radiation belt enhancements causing dramatic changes in the space weather environment can also be realistically simulated using the global magnetospheric model response to solar wind input and the resulting radiation belt modifications calculated from a submodel.

Ground-based Investigations

The spaceborne observations of the ISTP/GGS satellites are complemented by ground-based observations that remotely sense the ionospheric base of the magnetosphere. Along with the low-altitude measurements from FAST, the ground stations provide the observational signature of the final link in the Sun-Earth connection chain, the flow of mass and momentum, and energy dissipation in the Earth's atmosphere. This capability of continuously monitoring the flow into the terrestrial atmosphere is an essential contribution.

Four separate investigations constitute the set of ground-based instruments in the GGS program. The Sondrestrom incoherent scatter radar is located in Greenland. The Super Dual Auroral Radar Network (SuperDARN) of high-latitude HF radars has been developed and operated with funding from Britain, Canada, Finland, France, Japan, South Africa, Sweden and the US.

Also included is the Canadian Auroral Network for the Origin of Plasmas in the Earth's Neighborhood Program Unified Study (CANOPUS), comprised of magnetometers, riometers, meridian photometers and all-sky imagers. This network acquires ionospheric convection patterns over large areas of both polar regions. Finally, the SESAME project, operated by the British Antarctic Survey, contributes ionospheric sounder, VLF, Fabry-Perot interferometer, magnetometer and riometer measurements from its station in the Antarctic.

Vantage Points Provided by the Combined Assets

Heliospheric Configurations:

Foldout 2, Figure G illustrates a typical conjunction that will occur frequently between ACE, Geotail, and Wind while the latter is executing the sequence of distant prograde (DPO) orbits. Wind, with Geotail and other near-Earth spacecraft, will form a large baseline normal to the Earth-Sun line for the measurement of coherence lengths and geometries of large-scale interplanetary structures. The topologies of important structures such as interplanetary reconnection layers, interplanetary shocks, flux ropes, the heliospheric current sheet, planar magnetic structures, and shocks internal to magnetic clouds will be investigated for the first time on spatial scales and in directions never before available.

Nightside Magnetosphere Configurations:

By the fall season of 2001 and of subsequent years, a unique and scientifically powerful constellation of spacecraft for the studies of magnetosphere substorms will be assembled when the Polar apogee position arrives near the equator (Foldout 2, Figure A). One of the great unsolved problems of magnetospheric physics is the position and the mechanism for the explosive release of energy during these storms. The Polar equatorial position will be up to 9 R_E while the Geotail spacecraft will be located in the range of 10 to 15 R_E. In addition, the Cluster spacecraft will make north/south cuts through the plasma sheet and several GOES and Los Alamos geosynchronous spacecraft in equatorial orbits at 6.6 R_E will complete the array to be used for probing of the substorms. The position and timing for the substorms will be provided by mappings of the auroral brightenings into the equatorial plane as viewed with the Polar and IMAGE spacecraft. FAST will be able to provide in situ observations of the energy flow and particles producing the optical emissions.

The set of spacecraft are well positioned for these substorm studies because it is in the region between 6.6 and 20 R_E where the geomagnetic field evolves from a dipolar to a tail-like configuration. The spacecraft would be able to intercept the flows of plasma energy and the violent changes in the magnetic fields which occur. This is the region where large pressure gradients are expected to stimulate a rapidly growing instability. The actual dimension of the instability region is thought to be about 1 R_E and, thus can be expected to be directly encountered by one of the spacecraft several times per year. Such encounters would be the "jewels" of substorm research because the direct measurements could be used to identify the instability and focus theoretical efforts accordingly. Current thinking is that at least some of the substorm onsets occur in the ring current at radial distances in the range of 6 to 12 R_E.

Dayside Magnetosphere Configurations:

In the spring of each year, Polar, Geotail, Cluster, and IMAGE will be sampling the magnetosheath in complimentary ways (Foldout 2, Figure B). This represents an unprecedented opportunity to address questions about reconnection, plasma transport, and mechanisms responsible for magnetic pulsations in the Pc-1 to Pc-5 frequency ranges. Of particular interest for the GGS extended mission is the combination of Polar's north-south "skimming" orbits of the dayside magnetosphere, and Geotail's east-west cuts within or near the same region. Both spacecraft will spend long times (3-7 hours) in the layers where reconnection is taking place or where its direct dynamical consequences can be detected. Also fortunate will be the position of Cluster in the high-latitude reconnection regions near and poleward of the cusp and the simultaneous magnetopause imaging from IMAGE. The FAST satellite will observe these flux tubes at low altitude to observe the injected plasma. Future SEC mission plans do not place spacecraft assets in this global configuration ideal for confirmation of large-scale reconnection processes.

The state-of-the-art mass spectrometers and 3-D electric field and magnetic field instruments on ISTP/GGS make it particularly suited for studies of the dayside boundary layers (see section VII for a listing of the instrument capabilities). Previous missions have done an excellent job in this area but left some questions unanswered because of limited energy or temporal resolution in key plasma regimes or because the electric field information was not available. Figure 3 is an example of multiple Polar/TIMAS and MFE encounters with the magnetopause (~1900 and 0100 UT) and demonstrates the capabilities of the recently restored TIMAS instrument with respect to these encounters. The magnetic field intensity indicates compression (increase) in magnetic field strength (100 nT rather than the usual 10 nT) associated with increased solar wind pressure. Magnetospheric plasma is characterized by its high temperature and significant energetic O^+ component. Magnetosheath plasma are broad distributions of H^+ and He^{++} (after ~19:00 and before ~01:00 UT). ISTP/GGS will be able to resolve energy spectra inside and outside of the magnetosphere, and at times, inside and outside of the bow shock. Such observations will, if the IMF orientations are appropriate, provide, for the first time, direct tests of the well-known Fermi acceleration mechanism.

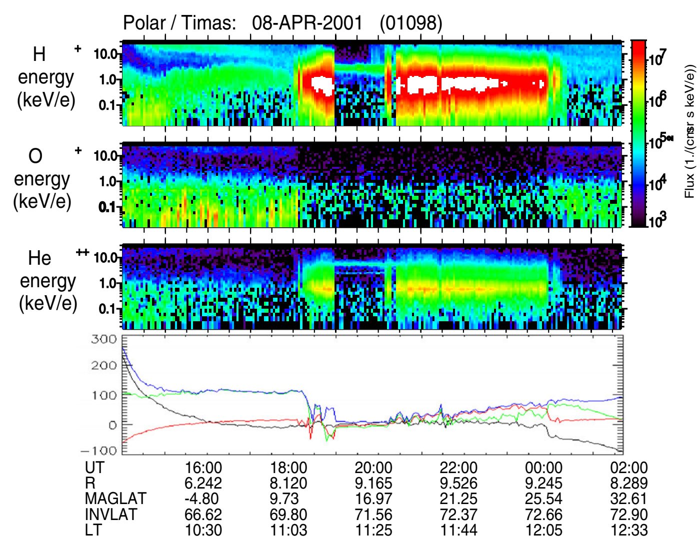


Figure 3. Polar/TIMAS and MFE encounters with the magnetopause (`1900 and 0100 UT). ITSP/GGS will be able to resolve energy spectra inside and outside of teh magnetosphere, and at times, inside and outside of the bow shock. The state-of-the-art mass spectrometers and 3-D electric field and magnetic field instruments on ISTP/GGS make it particulary suited for studies of the dayside boundary layers.

Relationship to the Solar Cycle

The proposed research spans solar activity maximum and approach to solar minimum (see Foldout 1, Figure K). Figure 4 is a plot comparing the annual solar sunspot number (yellow) with the number of days the Ap index exceeds a value of 40 (red). Statistically there are a greater number of geomagnetically disturbed days during solar cycle decline as compared to the approach to solar maximum. In fact, the peak in geomagnetic activity often lags solar maximum by several years. For ISTP, the solar maximum period yielded spectacular solar science results (c.f., SOHO senior review proposal). For ISTP magnetosphere investigators, it is the declining phase that is expected to bring the most important breakthroughs in understanding extreme geoeffective events.

Indeed, the magnetosphere's energetic particle spectrum exhibits very different behavior during the solar maximum, declining and solar minimum phases of an 11-year solar cycle (Figure 5). We found solar maximum to be a source of powerful transient events and coronal mass ejections that result in a commensurate response from the geospace environment. These aperiodic disturbances can cause nonrecurrent geomagnetic storms if the solar effluents reach the Earth. On the other hand, during the declining phase the solar corona is characterized by large transient equatorial holes which are sources of strong solar wind streams and consequent CIRs that can persist for several solar rotations. Such streams drive recurrent geomagnetic storms and produce substantial enhancements in the Earth's radiation belts. We note that the years from 2002 to 2005 should be the time of the strongest high-speed solar wind stream activity.

Whether investigating the special ISTP events associated with explosive or recurrent solar behavior, or analyzing the sometimes unpredictable response of the magnetosphere during more quiet times, the ISTP/GGS assets are a fundamental element of the global approach to understanding Sun-Earth connections as a system. The next several years will put that approach to the test as we complete nearly a full solar cycle. This proposal reflects our intent to use the assets of ISTP and of the many collaborating missions to understand the similarities and differences between the solar maximum and the approach to solar minimum conditions for the Sun, the interplanetary medium, and the magnetosphere-ionosphere system.

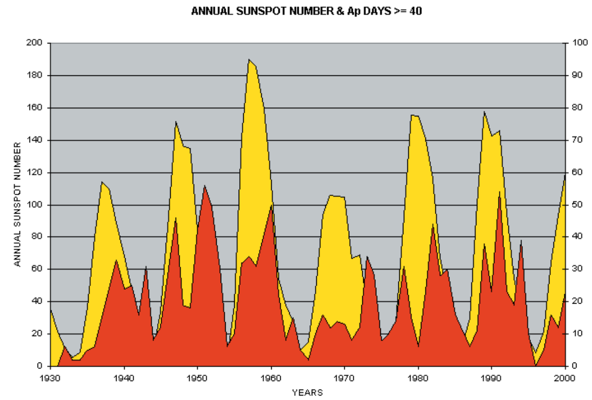


Figure 4. Comparison of solar sunspot number (yellow) with the number of geomagnetically active days (red). Because solar cycle decline is typically associated with a greater number of geomagnetically active days per year, we have every reason to expect frequent and strong activity during the upcoming extended mission period. (Graphic prepared by Joe Allen.)

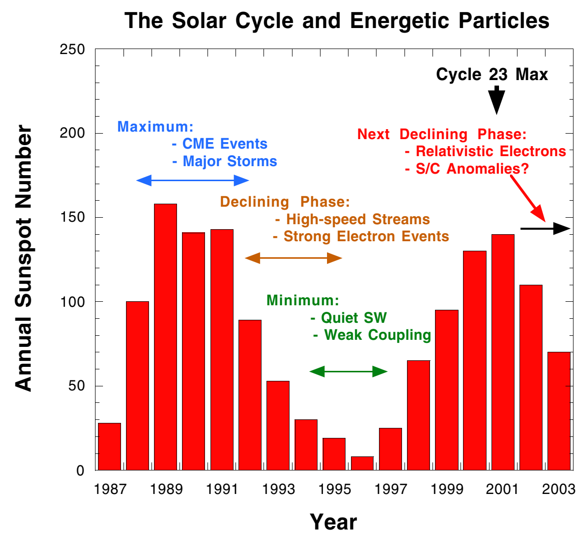


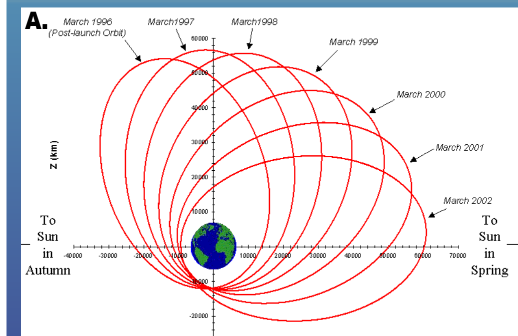
Figure 5. The magnetosphere's energetic particle spectrum responds differently during the phases of an 11-year solar cycle. The role of ISTP will be to understand how the solar wind-magnetosphere-ionosphere coupling differs during these phases. (Graphic prepared by Don Baker.)

ISTP/GGS is the Right Thing in the Right Place at the Right Time

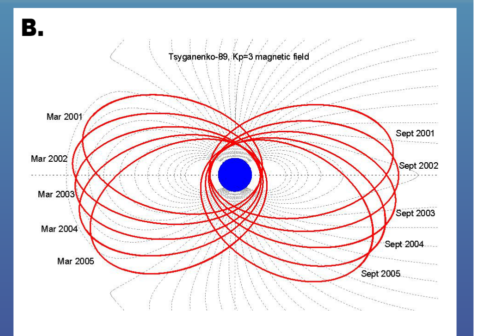
THE ORBITS PLACE THE SPACECRAFT IN THE HEART OF THE ACTIVE REGIONS

POLAR

then...



now...



The New Look for Polar

Polar's orbit apogee has evolved equatorward so that over the next 5 years it will reach midnight equatorial latitudes each Fall and noontime equatorial latitudes each Spring. Polar will assume some of the original EQUATOR spacecraft objectives envisioned for the OPEN program.

Key Measurements made possible by the new orbit

- Substorm ignition during energetic particle injection events at L=4 to 9 R_E
- Dayside merging
- Radiation belt traversals with full fields and particle measurements
- Dual hemisphere imaging

Science Promise

- Understand the relevance of reconnection, current disruption and ballooning instabilities in the substorm onset process
- Establish which are the controlling reconnection processes and quantify their relative importance for system dynamics
- Understand radiation belt time variations and their direct connection with solar variability
- Determine ring current ion transport and loss as a function of solar input
- Quantify the influence terrestrial source plasmas have on magnetosphere dynamics

The New Look for Wind Orbits

With its new strategic orbits – the Distant Prograde Orbit (DPO) and the Earth Return Orbit (ERO) – Wind will explore new regions of space. Wind will be at greater distances from Earth then ever before and in a new direction, normal to the Earth-Sun line.

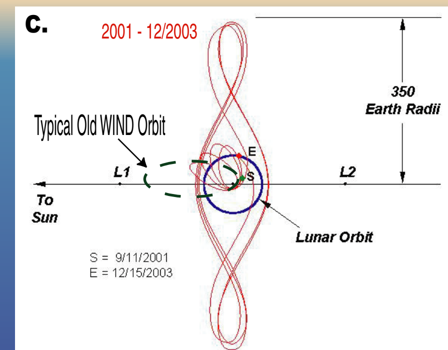
Collaborating Mission Key Measurement

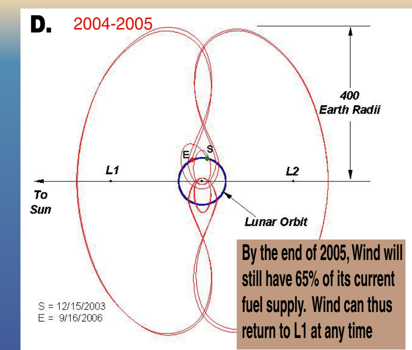
ACE/SOHO at L1 with Geotail near Earth	Interplanetary structures on meso-scale lengths for the first time
Polar, Cluster, Geotail in inner magnetosphere	Response of the deep tail during substorms - distant tail reconnection, tail breakup, and structure
Ulysses	Full 3D tracking of CMEs by Ulysses URAP and Wind Waves

Science Promise

- Develop 3D models of large interplanetary structures such as magnetic clouds, shocks, flux ropes, reconnection layers, etc.
- Improve 3D models of actual solar wind input at Earth for geospace-response modelers
- Delineate deep magnetotail boundary regions and magnetotail response to substorm processes
- Understand CME shock propagation, CME interactions, and relationship to solar eruptive events

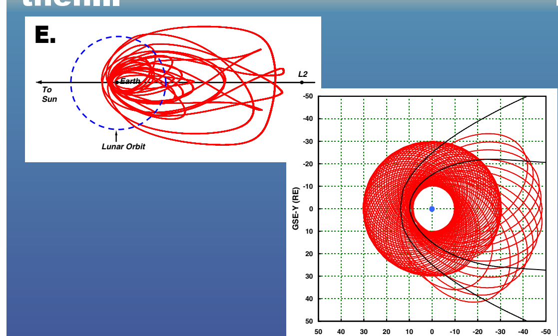
WIND



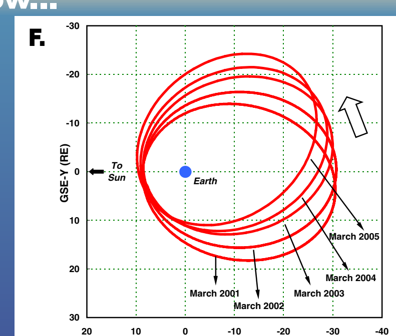


GEOTAIL

then...



now...



The New Look for Geotail

With no maneuvering fuel, the Geotail orbit will only precess; however its position relative to Polar will enable many new two-point measurements at separations between 2 and 10 R_E.

Key Measurements

- Rapid substorm flows observed tailward of Polar
- Low latitude boundary layer measurements near Polar
- Magnetotail plasma sheet as input for the ring current
- Near-Earth interplanetary particle and field measurements for comparison with Wind and ACE

Science Promise

- Determine the relative importance of the solar wind and ionosphere as magnetospheric plasma sources
- Determine how the ring current intensity depends upon the plasma sheet density, and how the plasma sheet density is affected by the solar wind.
- Better define reconnection in the tail and in the near interplanetary medium
- Better define the scale of magnetotail bursty bulk flows with Polar
- Define intermediate scale sizes in the interplanetary medium with Wind and ACE.

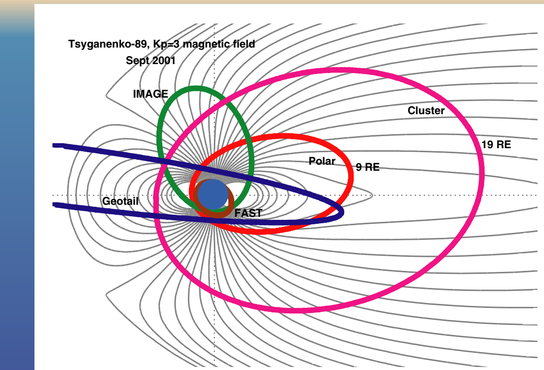
IDEAL CONFIGURATIONS FOR ANSWERING FUNDAMENTAL GEOSPACE QUESTIONS

NIGHTSIDE EQUATORIAL OPPORTUNITIES

Typical meridian-plane projections of key spacecraft orbits in the magnetosphere beginning late 2001. The Polar apogee will have moved to the equatorial region near 9R_E in the midnight sector from which vantage point simultaneous observations of substorm instabilities and onsets will be made with Geotail, with the Cluster spacecraft as it makes north-south cuts through the plasma sheet near 19R_E, and with IMAGE as it views the polar aurora.

Science Promise

- Progress in understanding substorm instability and onset mechanism
- Ionospheric ion outflow trajectories in the lobes
- Equatorial storm plasma injection and loss

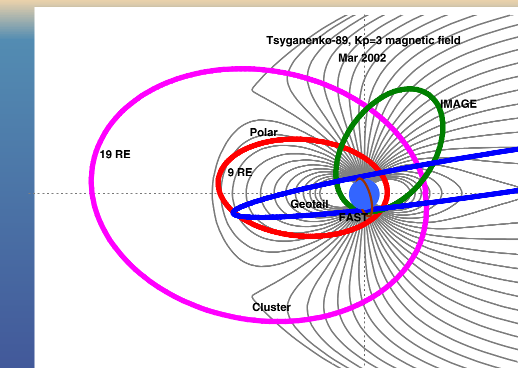


DAYSIDE RECONNECTION OPPORTUNITIES

In the Spring of each year (shown here in March 2002), Polar, Geotail, Cluster, and IMAGE will be sampling the magnetosheath and magnetopause in complementary ways. There will be unprecedented opportunities to address reconnection, plasma transport, and mechanisms responsible for Pc-1 to Pc-5 magnetic pulsations. These conjunctions will be of particular importance for reconnection studies because Polar's north-south skimming orbits of the dayside magnetosphere will be near Geotail's east-west cuts. Both spacecraft will spend long times in the layers where reconnection is taking place.

Science Promise

- Simultaneous reconnection measurements from two orthogonally orbiting spacecraft
- Improved plasma transport and magnetic pulsation models

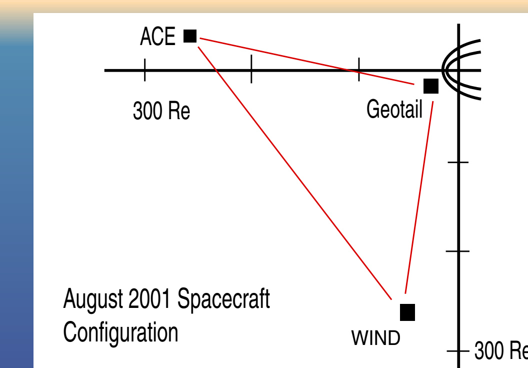


MULTIPOINT SOLAR WIND INPUT

While Wind is executing the sequence of new Distant Prograde (DPO) Orbits, ACE, near L1, and Geotail in the solar wind will form with Wind a large triangular baseline from which to make simultaneous measurements of interplanetary structures on a scale and with a spacecraft configuration never before possible. The 3D topologies of magnetic clouds, interplanetary shocks, interplanetary reconnection layers and other large-scale structures will be investigated for the first time.

Science Promise

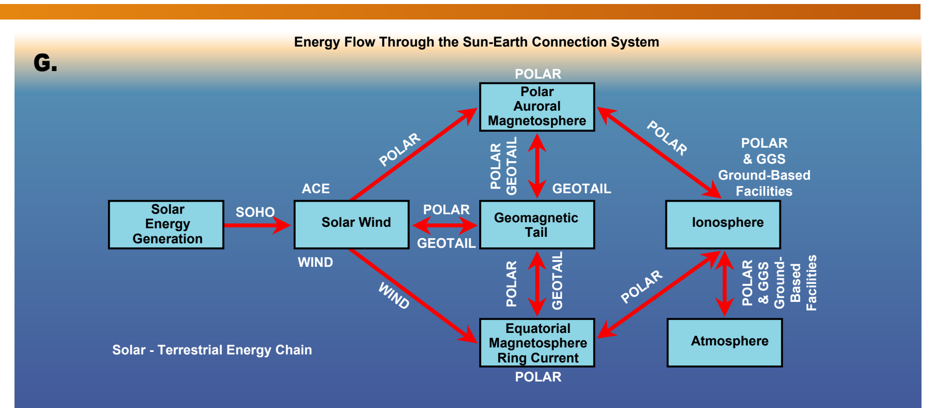
- Topologies of important interplanetary structures
- Improved solar wind input functions
- 3D tracking, with Ulysses, of CME-driven shocks



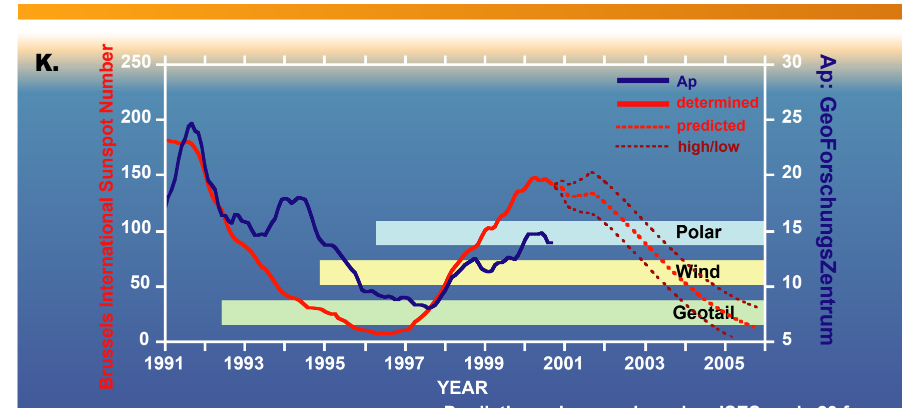
THEORY, MODELING AND GROUND BASED COMPONENTS

The theory, modeling and groundbased components form an integral part of ISTP. One of the great successes of the ISTP program has been the development and utilization of comprehensive MHD simulations that provide a global context for the widely-spaced ISTP observations, from distant spacecraft to groundbased observatories. The theory efforts have not only provided realistic global simulation movies of the magnetosphere and high latitude atmosphere and ionosphere response to actual solar conditions, but also provided key insights into the origins of plasmas in the Earth's neighborhood.

The extensive groundbased network of observers completes the last element in the ISTP Sun-Earth connection. The chains of magnetometers, radar, and optical cameras which now gird both poles have allowed quantitative comparisons between the modeling simulations and the actual measurements of auroral displays, magnetic fluctuations and ionospheric convection.



ISTP/GGS COVERAGE OF A FULL SOLAR CYCLE



Beginning early in 1996, near the end of the previous solar cycle, all of the originally-proposed ISTP spacecraft – Geotail, Wind, Polar and SOHO - became operational. With the conclusion of the currently-proposed extended mission, nearly a complete solar cycle will have been monitored by a suite of spacecraft with an unprecedented array of instrumentation. If previous history is any judge, the declining phase of the solar cycle will be an extremely exciting period of time, characterized by complex solar ejecta, high speed solar wind streams, unusually large geomagnetic storms, and possibly the largest solar energetic particle events.

Science Promise

- Expansion of the systems science approach of geospace characterization to the dynamic processes associated with the decline of the solar cycle

B. Science Objectives for the Extended Mission

Program Element 1. Extend the Systems Science Approach Describing the Dynamic Processes Associated with the Decline of the Solar Cycle

General problem:

The strongly non-linear response of the magnetosphere to the solar wind and its coupling with the ionosphere is perhaps the most critical element determining the geo-effectiveness of solar disturbances. Understanding this response requires a synergistic interaction between the end-to-end observations of a variety of events and the continuous improvement of physics-based simulations.

Recent work:

There is no question that enormous progress has been achieved from the cartoons and the steady state models of the seventies to today's data driven dynamic models. Our primitive, static characterizations of geospace have been replaced by highly dynamic visions of a complex, interacting environment. The several ISTP/GGS supported modeling efforts have yielded an array of simulation tools ideally suited for further 3-D imaging of the temporal evolution of the heliosphere-magnetosphere system (see section IV on ISTP's accomplishments). The 3-D, global, dynamic models have utilized actual data from ISTP/GGS as input to the code. The models then balanced as well as possible the model results against the space and ground based ISTP measurements and sought ways of improving the physics in the models to better characterize the system.

Problem to be addressed during the next 4 years:

Utilize the declining phase of the solar cycle to test the global simulation models against the effects of high speed streams with their resultant relativistic electron events.

Topics:

1) Further support the development, and use of, the integrated "full physics," global simulation models that have interpretation and/or predictive capability through the declining phase of the solar cycle.
2) Collect and recast the long-term ISTP statistical and empirical databases into forms necessary for modelers to accurately represent dynamic boundary conditions and to validate the physical processes represented within the codes.

Approach:

The global understanding of the Sun-Earth system has been built event-by-event by acquiring multi-satellite observations from key regions of geospace and using the theory models as an organizing unit for the data. The experimental and theory and modeling components of ISTP plan to further coordinate their efforts during the extended mission to:

- Provide dynamic physics based models, versus empirical simulations, of solar cycle declining phase geophysical processes, with a focus on cause-and-effect understanding.
- Analyze and integrate the physics underlying dynamic and complex events observed simultaneously in diverse geospace regions.
- Perform the data synthesis and data dissemination useful for modeling purposes.
- Be a springboard for the development of predictive codes for potential space weather forecasting applications, enabling and supporting SEC objectives such as the Living with a Star initiative.

A new area of concentration for ISTP's theory and modeling efforts will be toward understanding the entry of solar energetic particles (SEPs) into the magnetosphere, particularly the inner magnetosphere. Inner magnetospheric energetic particle fluxes increase during storms. While it has been established that SEPs can penetrate the magnetosphere [*Fennell*, 1972], their contribution to the observed fluxes is not clear nor is it clear how SEPs circulate, and exit the magnetosphere [*Gussenhoven et al.,* 1996]. It has been suggested that waves within the inner magnetosphere accelerate the observed high-energy particles [e.g., *Hudson et al.,* 1997]. This mechanism requires a seed population of high-energy particles in the inner magnetosphere but the origin of this population is also unclear. ISTP/GGS will simulate the entry of SEPs into the magnetosphere by launching high-energy particles into a time-evolving MHD simulation field. Quantitative comparisons will be made with high-energy particle observations from Polar, Geotail, and Sampex. The results will allow us to determine whether the high-energy particles observed in the magnetosphere, and those arriving at the inner magnetosphere, are contributed by the solar wind or accelerated internally (e.g., through wave-particle interaction). If the internal acceleration is important, the seed population will be identified and maps will be created of the accessibility of different regions of the magnetosphere to high-energy particles.

Another area of concentration will be toward providing the statistical and empirical databases necessary for modelers to accurately represent dynamic boundary conditions and to validate physical processes represented within the codes. Because the ISTP/GGS missions are mature and long-term databases of calibrated measurements exist for a variety of solar input conditions, there are several observation/modeling integration projects that can be completed within the next few years. All will contribute to the community resource aspect of ISTP. Most important are the variety of ISTP measurements recently identified by the space physics community as critical to the further development of predictive models, i.e., total ion outflow, field-aligned currents, electron precipitation rates, etc. [c.f., the GEM initiatives]. For example, several efforts have produced statistical and empirical maps of ionospheric mass in the magnetosphere as functions of IMF and solar wind parameters [*Collin et al.,*1998, 2001; *Su et al.,*1998*; Rowland et al.,* 1998*; Lennartsson et al.,* 2000*; Giles et al.,* 200l]. These datasets will be modularized into a form suitable for use within current global simulations. The terrestrial-source mass characterization will be given in terms of empirical parameters local to the ionosphere-magnetosphere boundary, such as field-aligned currents which act to couple the magnetospheric and ionospheric plasmas as a consequence of the boundary conditions imposed.

Discussion:

The art of modeling complex systems implies making certain approximations while keeping the essence of the system. Models require continual improvement and testing against data for as many different solar input cases as possible. Foldout1, Figure G schematically illustrates the connection between the ISTP/GGS observations and the solar terrestrial energy chain as simulated by the supported global modeling efforts. Energy flows from the photosphere and corona, through the interplanetary medium to Earth's vicinity where it interacts with the geomagnetic field and atmosphere. Note the connection to ISTP/GGS measurements both for boundary condition input and for ground truth validation. This is the glue holding together the modeling and observational components. The next 5 years of the solar cycle will provide many new case studies for the ISTP/GGS theory and modeling effort.

Figures 6 and 7 illustrate two examples of how the link between theory and observations will be expanded during the extended mission. Figure 6 is from a University of Maryland, Lyon-Fedder-Mobarry (LFM) global magnetospheric code model simulation of a substorm. Simulations of this type provide the only dynamic, global images of the entire Sun-Earth connection system during a given event. The figure shows the magnetospheric current and magnetic field structure just before, at and after substorm onset on March 9, 1995. This particular simulation is displayed rather than more recent ones because it first demonstrated the critical role of the near-Earth tail, between 6-15 R_E, in initiating substorms. The decrease of crosstail current at 8-10 R_E indicates its diversion along field lines and into the ionosphere. The magnetic field deflection in this region, due to these parallel currents, is prominent as well. The simulation indicates the current diversion and onset are associated with the penetration of the electric field in the vicinity of 6-10 R_E.

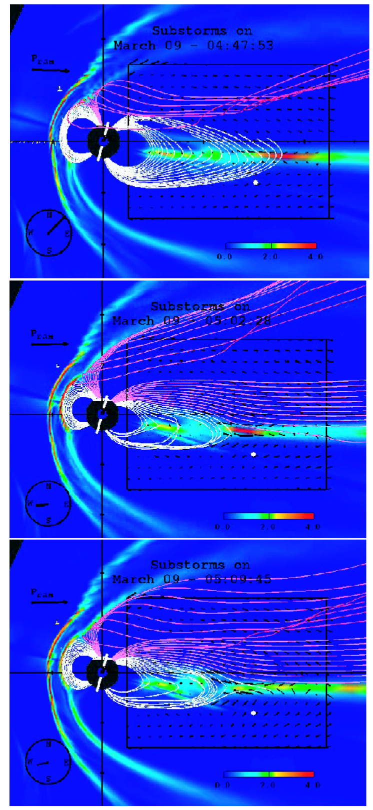


Figure 6. UMD LFM simulation results showing the structure of perpendicular current (normalized by B) on a Meridian plane before (- 2 min), at (+2 min), and after (+10 min) substorm onset. Field lines originating in the northern hemisphere at noon and midnight illustrate the magnetic field structure. These simulations provide the only dynamic, global images of the entire sun-earth connection system for a given case study interval.

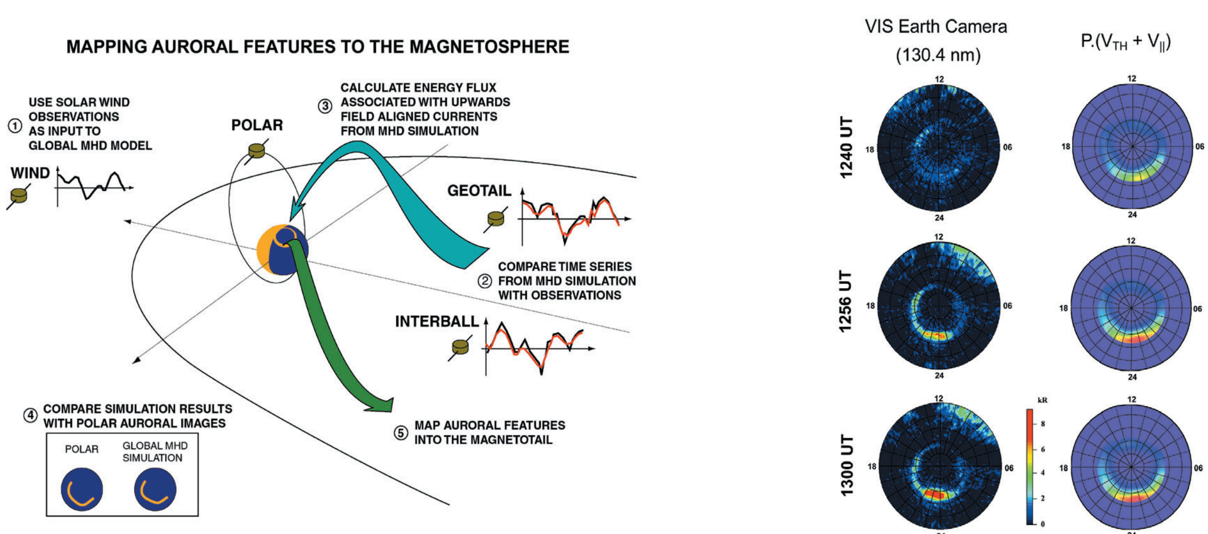


Figure 7. ISTP's system level approach transfers observational knowledge into physics based MHD models. Closure, and further knowledge, is provided by comparing MHD simulations of specifc events to in situ observations of those events. A recent example is the Ashour-Abdalla et al., 2001 investigation of the late growth phase and expansion phase of a large magnetospheric substorm. The schematic to the left illustrates steps within the data and modeling interaction. To the right are simulated energy flux images of the aurora along with the corresponding Polar/VIS observations.

This simulation also illustrates the importance of the close interaction between theory and observations in the ISTP/GGS program. The simulations provide context for the observations while the observations are vital for code validation. When the output of the LFM code was tested against ISTP/GGS ground-based observations, while relatively good agreement with the CANOPUS magnetometer chain observations was found, serious inconsistencies with riometer data arose. The times of the major discrepancies coincided with times that the electrojet current was very large. This led to improved representation of the physical mechanisms within the appropriate part of the code and eventual successful "ground truth" testing. It is this continual iteration of the simulations against the data with each new event observed that yield quantitative and predictive geospace models of the caliber needed for the Living with a Star initiative and the future prediction of space weather events.

Figure 7 is a direct comparison between images from the Polar/VIS camera and a global MHD simulation by UCLA's Space Simulation group and was used to investigate the late growth phase and expansion phase of a large magnetospheric substorm that took place on December 22, 1996. The schematic illustrates the process. Solar wind input data from the Wind spacecraft was applied as the upstream boundary condition for the MHD code. The results of the MHD simulation were calibrated by comparing Geotail and Interball measurements against the model output at several intervals of time. The energy flux in the auroral zone was calculated and compared with the imaging observations from Polar. Notice that the enhancements in the calculated energy flux show a good correlation with the timing of auroral brightening and the motion of the auroral display. The power flowing into the ionosphere in the simulation was also in good agreement with that determined from Polar/UVI empirical models of auroral power.

These tasks point out the essential modeling requirement of a realistic set of boundary parameters. At the lower boundary these parameters are the field-aligned currents and the ionospheric conductances which couple the ionosphere and the magnetosphere. With the new orbit configuration of Polar, conjugate auroral regions in the northern and southern hemisphere will be imaged simultaneously. This will provide better input parameters to the ISTP supported AURORA-AMIE-TIMEGCM model [*Rees et al.,* 1995. The model will yield more accurate energy input rates from the magnetosphere to the ionosphere/atmosphere, and ionospheric conductance patterns given the continuous time-dependent conjugate measurements. In combination with worldwide ground-based magnetometer data and ionospheric convection data, the global distribution of field-aligned currents can be determined. The conjugate asymmetric characteristics of these parameters at different seasons and for different interplanetary magnetic field vectors will allow the models to more accurately describe the physical processes that, for example, govern the evolution of substorms. Do these occur simultaneously in both hemispheres and do the models correctly predict the conjugate location?

The outer boundaries of the global models will also benefit from the new spacecraft configurations. The upstream boundary is commonly simulated as a flat surface, and all perturbations seen at the solar wind monitor are assumed to make it to Earth. However, as we know, the solar wind and IMF are quite structured, and this inhomogeneity should be taken into account. The presence in the solar wind of multi spacecraft, widely separated, such as Wind, Ace, and Geotail, will greatly help us understand the 3-D properties of the solar wind and IMF. The improved level of input to our MHD simulations will result in a more realistic description of the interaction of the solar wind/magnetosphere/ionosphere system.

ISTP/GGS will continue to work to further integrate theory and observations and the synergistic interaction between experimenters and modelers. The ISTP/GGS workshops have been an excellent forum for comparison and verification of the model predictions with in situ observations. These opportunities for close dialogs between modelers and experimenters can encourage and support logical improvements to the global models already in use and encourage the use of new ISTP/GGS empirical descriptions of source parameters.

Program Element 2: Understand the Dynamic Processes Associated with the Equatorial Region of 2-30 R_E.

2A. Quantify the Relative Influences that Solar and Terrestrial Source Plasmas Have on Dynamic Equatorial Processes

General problem:

Discriminate between solar wind and terrestrial sources of plasmas and understand their flow within the system.

Recent Work:

The discovery of a significant, persistent flux of Polar wind escaping to the lobes of the magnetosphere showed that terrestrial outflow plays a more significant role than predicted. The region dominated by these outflows regularly extends well beyond the plasmasphere and, with sufficient solar wind influence, can at times dominate all but the far boundary layers and distant magnetotail [*Moore et al.,* 1999, 2000]. Recognition of the importance of the terrestrial source does not eclipse the importance of plasma entering directly from the solar wind [i.e., *Shodhan and Siscoe, 1996; Terasawa et al., 1997, Ashour-Abdalla et al., 1997, 1999*], which, at times, drives the system flow and energetics. These Polar, Geotail and modelling results have seemingly divided research attention between finding solar wind injections into the system and understanding the extent of the ionosphere output. However, the first global circulation model to include both plasma sources [*Winglee*, 1998] has demonstrated the coupled nature of the system in which the extension of the ionosphere into the magnetosphere essentially extends the mass and energy load on the solar wind. The combined influences, under quiet and active conditions, of these two sources of plasma on the dynamics, composition and wave-particle interactions within the critical near-Earth equatorial region need to be identified and quantified observationally, and validated against a new generation of global circulation models.

Problem to be solved during the next 4 years:

To what extent does the flow of solar and ionosphere plasma, separately or together, directly influence equatorial magnetosphere dynamics, act as a catalyst for dynamical processes, or simply exist as a moderating influence on the dynamics?

Topics:

1) When and how much of the magnetosphere is taken over by ionospheric plasma as its influence expands in response to solar energy inputs? Does the terrestrial plasma "geosphere" coherently expand or diffusely mix with solar wind plasma under dynamic conditions?
2) What are the source-to-destination flow paths for solar wind entry plasmas? To what extent are these paths mutually exclusive from those of the terrestrial source?
3) How is solar wind energy coupled into topside ionospheric heating that is effective in extracting ionospheric plasma into the magnetosphere?
4) To what degree does heavy ion outflow from the ionosphere precede and/or follow substorm and storm onsets?
5) How much oxygen escapes from the magnetosphere? How much escapes to the upstream region? What is its overall circulation?

Approach:

The future orbit orientations of Polar, Geotail, FAST, and Cluster, for nightside and dayside sectors, are ideal for tracing both the solar wind and the terrestrial plasmas from their entry points, through any acceleration processes, and on to their destination in the plasma sheet or beyond (Foldout 2, Figures A and B). Within this discussion we address the circulation of solar wind plasma and the entry and circulation of terrestrial plasma. The entry of solar wind plasma is discussed in section II-4B.

The Polar and FAST spacecraft combination is extremely important for understanding the supply of ionospheric plasma to the magnetosphere. FAST (350-4175 km) directly observes the initial heating and acceleration processes while Polar perigee passes (5000-9500 km) of the high-latitude region observes higher altitude acceleration processes. The meridional cuts of Polar and Cluster at 9 and 19 R_E will provide needed observations of plasmas entering the plasma sheet region from the lobe. Mass and flux dependent variations with activity should be apparent. Geotail studies have laid ample foundation for this [c.f., *Hirahara et al. 1996; Taguchi et al.,* 1998]. The dayside meridional cuts of Polar combined with the equatorial cuts of Geotail will allow tracing of periodic plasmasphere contributions.

Unique to ISTP are the fine angle/energy resolution measurements and level of sensitivity in the important thermal energy range offered by the Polar/TIDE and TIMAS combination. This in conjunction with the ability to identify the complete electric and magnetic field environment offers the best opportunity to complete the mapping of the terrestrial plasma source throughout its region of influence.

Discussion:

The magnetospheric regions accessible to nominal ionosphere outflows are illustrated in Figure 8. Shown are H^+ and O^+ particle trajectory paths in representative 3-D magnetic and electric fields for solar minimum conditions. The results for H^+ and O^+ are very different. The particles with the direct path toward the plasma sheet interaction regions are the relatively fast nightside H^+ particles and the relatively slow dayside O^+ particles. These travel adiabatically, intercepting the center plane at distances from ~32 to 45 R_E depending on the initial latitude. Upon encountering the neutral sheet, centrifugal trapping and nonadiabatic motion within the neutral sheet produce further energization and the stochastic earthward trajectory patterns typical of energetic plasma sheet particles [*Delcourt et al*., 1994].

These convection patterns are representative of only a single outflow situation – a few auroral zone latitudes, at two locations in local time, for a single energy and for quiescent conditions. Actual patterns are far more complex and variable. For example, colder polar cap protons and warmer nightside auroral zone O^+ will also contribute to the interaction regions under quiet conditions. The downtail distance for nightside originating O^+ will depend on the initial energy of the source population, with colder heavy ions contributing to mid-plane regions nearer to the Earth. Under the influence of a more stretched magnetic field, nightside O^+ would dominate as the source population with H^+ playing an increasingly smaller role. Rapid magnetic dipolarization could quickly change the contributing source population landscape.

The precession of the Polar spacecraft, which brings the 9R_E apogee down through the lobes to cut through the dynamic plasma sheet at successively higher altitudes, will allow the thermal and mid-energy range particle instruments to take the detailed measurements needed to quantify this mass flow under the dynamic conditions of solar cycle decline.

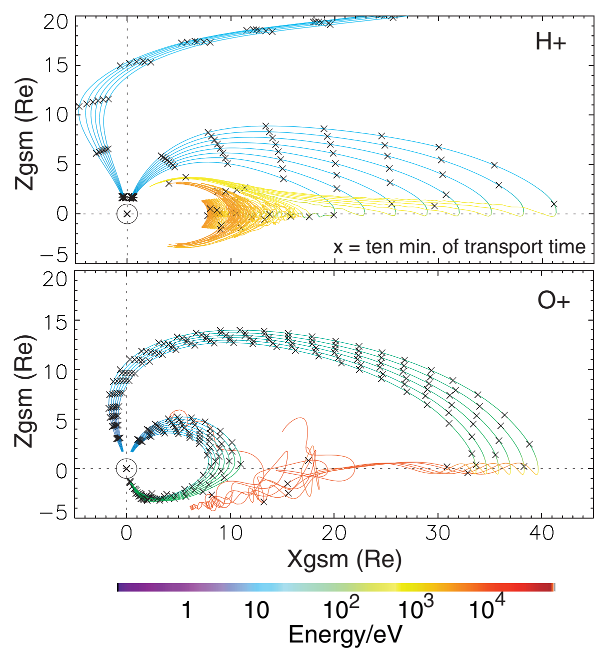


Figure 8. Calculated flow (not limited to convection) paths and energy evolution for 15 eV H^+ and O^+ field-aligned ions originating at peak auroral source locations. This illustrates the relative influence that dayside and nightside ionosphere source populations may have on plasma sheet dynamics. The calculations were performed with the Delcourt et al. [1994] trajectory code, Tsyganenko [1987] magnetic field for Kp=0 and Volland [1978] derived electric field using characteristic auroral source altitude and energy parameters of 1.8 R_E and 15 eV. Trajectories were arbitrarily discontinued inside of 10 R_E or at mirroring altitudes.

Understanding the changing mass flow must be joined with understanding the drivers controlling the outflow source parameters. The mechanisms that produce upwelling and accelerated high latitude thermal particles are not the same ones controlling the convection patterns. Disparate mechanisms respond to different solar wind drivers and with quite different delay times [*Giles et al.*, 2001]. Special emphasis will be given to Polar and FAST wave-particle observations to determine the phase space distributions of electrons and ions associated with solitary potential structures. We will be looking for both cause and effect of the solitary structures, and the presence or absence of electrostatic whistlers [*cf. Goldman et al.,* 1999]. Recent observations have shown evidence of intense ion heating [*Carlson et al.,* 1998; *Huddleston et al.,* 2000; *Catell et al.,* 2000] associated with solitary waves.

Use of the ISTP ground resources such as incoherent scatter radars (Sondrestrom, EISCAT), HF radars (SuperDarn), and AMIE can quantify the ionospheric energy budget, its contribution to ion and electron flows, and determine which coupling mechanisms dominate under varying solar input conditions. For example, the SuperDARN radars can be used to determine the electric field over large spatial regions and the visible and ultraviolet imagers on Polar to estimate ionospheric conductances. It is possible to estimate Joule heating rates within the ionosphere and determine their spatial and temporal variability (Figure 9). Ionospheric measurements of electron temperature in the topside F-region of the ionosphere show that temperature enhancements in the dayside oval and polar cap (cusp, mantle, low-latitude boundary layer) are due mainly to heat flux coming from the magnetosphere and not from the low energy flux characteristic of the electron precipitation in these regions. In related work, a model, quantifying magnetospheric loading and unloading has been developed to combine polar cap boundary estimates from Polar UVI and VIS images with radar-based maps of ionospheric convection. The model will be used to quantify the cycle of loading and unloading for different solar wind inputs and to calibrate global models of the magnetosphere.

Since solar plasma is known to leak into the magnetosphere and dominate at least the cusp regions and outer reaches, it is evident that ionospheric plasma must also leak out of the magnetosphere, where it is carried off downstream, representing a net loss to the Earth. Moreover, to the extent that the plasma sheet contains ionospheric plasma, routine shedding of plasmoids from the magnetotail must similarly represent a loss of plasma to the downstream solar wind. A quantitative assessment of these fluxes can be made in at least a statistical sense using the ISTP spacecraft, and the dependence of this escape on solar cycle will similarly be estimated.

The new equatorial orientation of Polar places the spacecraft at the dayside equatorial magnetopause every 18 hours during the spring months. In this configuration the low-latitude boundary layer, turbulent boundary layer and magnetosheath are sampled for periods ranging from several minutes to several hours. Analysis of low-energy data from the TIDE instrument on Polar reveal plasmaspheric-like ions within the turbulent boundary layer (Figure 10). Correlations of such observations in conjunction with IMAGE satellite observations of sunward extended plasmasphere

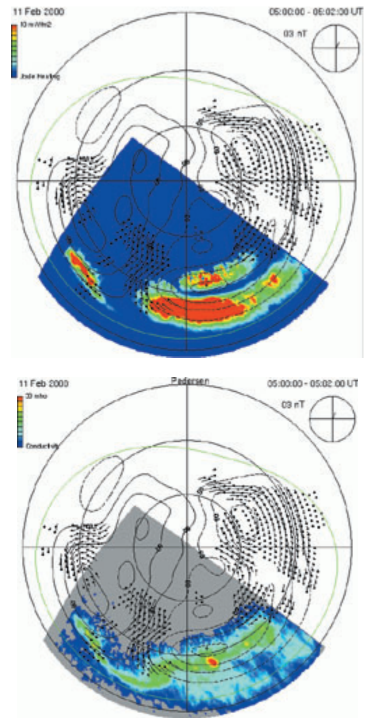


Figure 9. SuperDARN convection pattern with superposed ionospheric Pederson conductance (right) derived from VIS and superposed estimate of Joule heating (left) derived from $Q_j = \Sigma_p E^2$. Observations of ionospheric electric fields, current systems and conductivities can do much to specify energy flow into the ionosphere and to determine its impact on ion outflows.

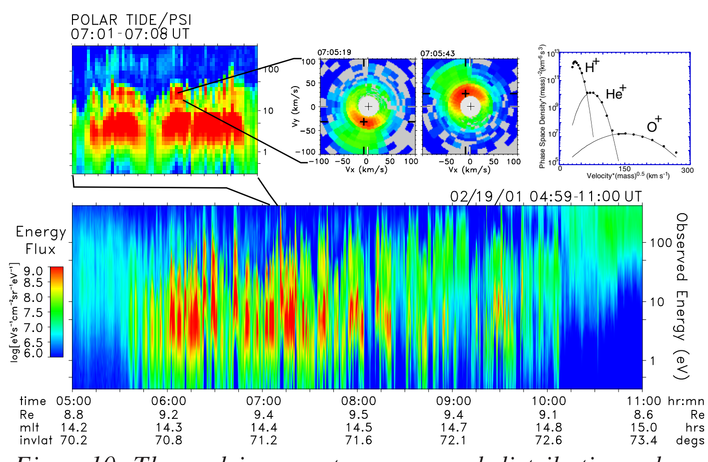


Figure10. Thermal ion spectrograms and distributions show circularly polarized waves near the dayside magnetopause accelerating plasmasphere-like ions to 30-40 km/s. Likely to be associated with the sunward stretching plasma tails observed by IMAGE, this indicates the presence of a convection path for plasmaspheric ions to the magnetopause boundary layer and the further acceleration needed to carry the plasma tailward, eventually to participate in plasma sheet dynamics. Without detailed thermal particle information, detection of these populations and determination of the plasma's originating source and flow characteristics is all but impossible.

tails will determine the contribution of this low-latitude terrestrial source to the high-latitude outflows under varying conditions. Trajectory modelling will be applied to the problem of understanding the subsequent circulation path and predicting its impact, if any, on dynamic processes.

The biggest challenge facing those interested in including realistic mass exchange mechanisms within their models is in the area of development resources. Most global circulation codes are based on a single MHD fluid and it is a significant task to include either an additional fluid for the ionospheric plasma, or to develop means of tagging parcels of fluid according to their boundary of origin in the system. Some global model development toward this end could be supported within ISTP under the desired funding scenario.

A significant step in global modeling development that can be supported under the nominal ISTP funding is the transition of the measurements into the local response specification models required by MHD modeling techniques; for example, the development of analytical specification of ion outflow as a function of solar driven inputs such as precipitation, field aligned currents, and local sunlight. Implementation of these local specification models within the global models would then follow under the auspices of other programs.

Similar considerations apply to understanding the solar wind source of plasma within the magnetosphere. The basic convection patterns and possible source locations have been established by comparison of observations with typical global circulation models. A great deal of statistical information exists documenting the energies, fluxes and composition of plasma throughout the system. Additional work remains before estimates of total influx under various solar input conditions can be agreed upon (see section II-4B for the discussion on reconnection).

If there is one realization that has come from the ISTP era, it is that the solar wind and the Earth's magnetosphere, ionosphere, and atmosphere form a complex plasma exchange system in which global dynamic behavior is affected by all of the individual parts. Considerable information on the "flow of mass" problem has been compiled. A primary ISTP goal for the coming years is to combine this information into a unified understanding of the dynamic flow.

2B. Determine Equatorial Storm Plasma Injection and Loss as a Function of Solar Input

General problem:

The traditional measure of geospace storms is the intensity of the ring current. The ring current is an electric current centered at the equatorial plane flowing around the Earth at geocentric altitudes of 2.5 to 6 R_E. Enhancements of this current are responsible for global decreases of the magnetic field measured at the surface of the Earth, which are known as geomagnetic storms. The main carriers of the storm time ring current are positive ions, which are injected into the inner magnetosphere and trapped by the geomagnetic field.

Although a strong southward interplanetary magnetic field is the prime instigator of magnetic storms, there is still much uncertainty regarding the conditions and mechanisms that enhance the ring current and control its recovery. Because conditions in the solar wind that lead to the injection of energetic particles into the ring current simultaneously affect a variety of geomagnetic phenomena, it can be difficult to determine which processes are causally related. Questions also remain regarding how closely magnetic storm behavior is related to magnetospheric substorms. The roles of electrodynamic coupling and precipitation losses into the ionosphere also remain topics of active investigation.

Recent work:

Several processes have been proposed to explain ring current enhancements: 1) the inward transport of plasma sheet particles by enhanced convection electric fields that occur in response to the imposed IMF electric field; 2) particle injections associated with substorms, 3) the diffusive transport of energetic particles due to magnetic or electric fluctuations, 4) the direct entry of ions from the midlatitude ionosphere to the ring current. All or part of these mechanisms can be correlated with the interplanetary disturbances associated with corotating interaction regions and coronal mass ejections (CMEs) which, in turn, have been shown to cause large geomagnetic storms [*Gosling et al.,* 1990; *Gosling*, 1993]. Figure 11 illustrates the connection between solar wind input processes and the magnetospheric consequences that can contribute to magnetic storm development. ISTP/GGS will resolve uncertainties in this picture by providing definitive particle and fields observations on the solar wind input, the magnetospheric convection, and the extent of losses due to convection, charge exchange, Coulomb collisions, and resonant interactions with plasma waves.

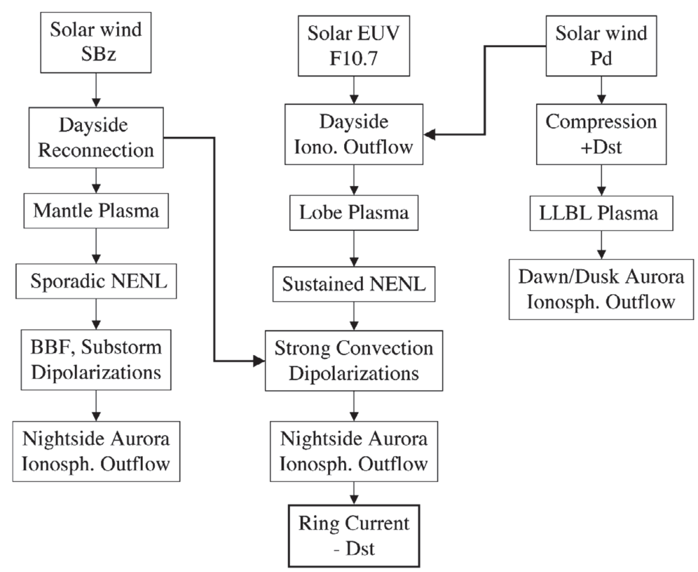


Figure 11. The connection between solar wind input processes and the magnetosphere consequences that can contribute to magnetic storm development.

The primary tool to indicate ring current strength is the Dst index, which exhibits a minimum during the main phase of a storm, usually followed by a two-phase recovery process. It has been suggested that the faster, early stage recovery process is dominated by O^+ charge-exchange losses to the atmosphere while the slower, later stage recovery is governed by H^+ charge exchange losses [*Hamilton et al.,* 1988, *Daglis et al.,* 1997]. *Takahashi et al.* [1990] have proposed that the two-phase decay process is from convective losses during the rapid recovery phase and charge exchange losses during the slow recovery phase. Modeling of these processes has produced mixed results with some stating that the fraction of ring current energy from O^+ charge exchange is reasonably adequate in creating the rapid recovery [*Jordanova et al.,* 1996, 1998] and others showing that it is not [*Fok et al.,* 1995; *Kozyra et al.,* 1998; *Chen et al.,* 1998, 1999]. These studies generally modeled a single storm so it was unclear whether storms at different phases of the solar cycle might exhibit different decay rates because of varying O^+ contributions to the ring current. *Liehmohn et al.,* [2000] have performed a modeling study to show that the charge exchange decay process, though important at solar maximum, is still overshadowed by the effect of convection outflow, a process not typically included in the earlier studies.

Problem to be solved during the next 4 years:

Determine to what extent and under what conditions storm recovery is controlled by the decay of cross-tail and magnetopause currents, to the convection of ring current ions out of the magnetosphere to H^+ and O^+ charge-exchange differences, or to enhanced wave-particle interactions. Identify conditions, if any, leading to ring current injections that do not lead to significant auroral activity to settle questions linking substorm to storm behavior.

Topics:

1) How much of the storm time ring current energy is deposited into the atmosphere and how much is lost by charge exchange or by convection out of the magnetosphere?
2) How important is the role of wave-particle interactions in the decay (or growth) of ring current plasmas.
3) How important are substorms in storm development? Are there convection-only events (SMCs) that produce ring current without any substorms?

Approach and Discussion:

ISTP/GGS will be able to resolve the uncertainties in storm dynamics by providing definitive particle and fields observations on the solar wind input, the magnetospheric convection, and the extent of losses due to convection, charge exchange, Coulomb collisions, and resonant interactions with plasma waves. The observations are needed for a variety of geomagnetic storm types to see what conditions are common to and different among them. As we move into the next solar cycle where the solar magnetic field polarity has reversed, we can expect the trailing portion of magnetic clouds to contain southward magnetic fields rather than northward fields. In this case we might expect greater field and plasma compression in the trailing southward portion that might lead to larger storms with a different character.

We need to explore variations in the hot O^+ component seen primarily on the dawn side of the equatorial magnetosphere after geomagnetic activity. This component appears to have two sources: a) direct injection on auroral field lines, and b) convection from the plasma sheet. Polar data can be supplemented with FAST and UARS data for this topic. However, Polar with its higher altitude, should occasionally transit the wave-particle interaction region directly leading to a better understanding of the mechanisms.

We can also learn a great deal about the dynamic distribution of plasma in the ring current by measuring the distortion of the magnetic field caused by the presence of the hot ring current plasma. This study requires measurements during storms of different strength and over a variety of local times, as a function of storm phase. The longer the mission continues, the more complete is our coverage at each local time as well as over the solar cycle where O^+ shows important variations.

The ring current injection/magnetic storm topics are well suited for application of Polar's equatorial imaging capabilities. Both the CAMMICE/ENA and the auroral imagers will be useful. Two types of ENA opportunities are created by Polar and IMAGE in collaboration. First, when Polar and IMAGE are at high latitudes simultaneous stereo ENA imaging of the ring current region will provide more detail on the structures and dynamics than either satellite alone. Second, when IMAGE is at high latitudes and Polar is in the ring current directly measuring the ion distributions and composition, the Polar observations provide "ground truth" measurements by which to invert the global IMAGE information. It is interesting to note that since IMAGE and Polar are unable to do ENA imaging within the electron radiation belts and therefore have about a 75 percent duty cycle for ENA imaging, the combination of spacecraft gives nearly complete temporal coverage. Later, with the launch of the first TWINS satellite, the first opportunities for three-satellite ENA tomography will begin. The Polar investigators experienced in ENA imaging plan to make the most of the opportunities to 1) time tag observational storm signatures as compared to Dst, and 2) compare the movement of energetic populations through varying locations as compared to model predictions.

The charge exchange ring current decay process causes the precipitation of energetic neutral atoms (O and H) near the equator [*Tinsley*, 1979, 1977]. Once the neutral O reaches the atmosphere some of it ionizes again from collisions, and then radiatively recombines to yield O emissions. The intensity of the equatorial aurora is then directly proportional to the O^+ contribution to the total ring current and can be used as a remote probe of ring current composition. Thus, ultraviolet imagery from Polar will help explain how and when energetic particles precipitate. An important observation would be the latitude at which the emissions occur and how this varies with longitude. Typically, arcs occur in symmetric belts at 10-15°geomagnetic latitude with intensities in the FUV are up to 400R at 130.4 nm and 20R at 135.6 nm [*Ishimoto et al.,*1992]. Another imaging opportunity relevant to storm dynamics is imaging of the global atmospheric O/N_2 ratio. When studied at low latitudes, the O/N_2 ratio and its variation provide a reality check for models of the thermosphere. At mid-latitudes, the ON_2 ratio can be drastically altered during strong geomagnetic activity providing a clear example of solar-wind magnetospheric interactions producing effects reaching into our atmosphere. Figure 12 shows the ratio of O/N2 (from the 1356 A and LBH-long filter) before and after the July 14-16, 2000 geomagnetic storm event. Deletion of O in the dawn sector after the storm is evident. The N_2 population is believed to be relatively stable, hence oxygen outflows from the thermosphere into the magnetosphere probably cause most of the variation. The opportunities for recording such data should increase during the current solar maximum and declining phase periods, when corotating interaction regions provide for extended storm periods.

Stable auroral red (SAR) arcs occur at mid-latitudes at altitudes of 450 km, have a brightness of up to 2 kR at 630 nm and a lifetime of days. Since they occur only during the recovery phase of magnetic storms, information regarding the ring current loss rate can be extracted from observations. The responsible mechanism is thought to be heat conduction or very low energy (<10 eV) electron flux, probably the high-energy tail of a Maxwellian distribution of an ionospheric thermal population [*Kozyra et al*., 1997]. The LBH emissions have a threshold for excitation of 8.5 eV and so the ultraviolet imager on Polar has a high probability of detecting SAR-arcs. Observations of SAR-arcs in the FUV could enhance our understanding of ring current loss mechanisms and how magnetic storms dissipate.

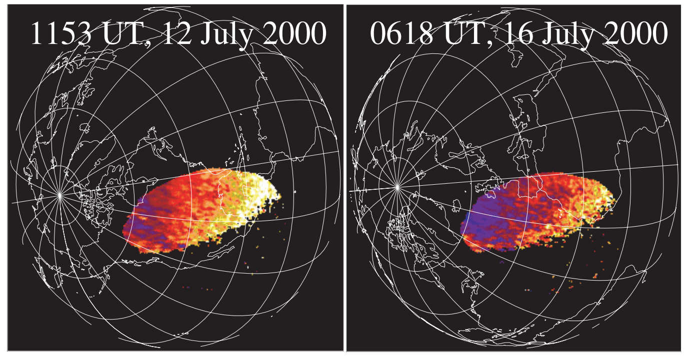


Figure 12. Images from Polar/UVI 1356 LBHI filter, O/N ratio, showing atmospheric oxygen depletion before and following the July "Bastille Day" event. Equatorial auroral intensity is proportional to the 0^+ ring current contribution. This and similar UV imagery from Polar will help explain how and when energetic particles precipitate.

2C. Understand Radiation Belt Time Variations and Their Direct Connection with Solar Variability

General problem:

There is renewed interest in isolating and understanding the mechanisms responsible for electron flux enhancements in the radiation belts that typically form during the recovery phase of geomagnetic storm periods. The interest in these events arises in part because of evidence that occurrence of these fluxes contributes to spacecraft operating anomalies or failures, especially at geosynchronous altitude. The prediction and mitigation of these effects should be possible when the causes of the flux enhancements are understood [*Baker*, 1996].

How does the relativistic electron population in the radiation belts vary over the solar cycle? There are two broad classes of mechanisms thought to explain the cause of relativistic electron enhancements observed in the inner magnetosphere; 1) internal acceleration mechanisms that rely on internal magnetospheric recirculation, and 2) mechanisms that rely on the presence of an external source and enhanced radial convection. Until now, the combination of spacecraft that can monitor both the internal dynamics and the external source mechanisms during an active phase have not been in place to adequately address these issues.

Recent work:

Much has been accomplished toward the identification of possible acceleration mechanisms using both observational and theoretical approaches. The Polar spacecraft array of instrumentation, along with other missions able to sample the radial B,L profile (GPS, HEO), have identified rapid electron flux enhancements as close as L=2. These observations have challenged established theories (large-scale recirculation) developed chiefly to explain observations at geostationary orbit. These in turn have led to suggestions of a variety of small-scale, fast recirculation mechanisms in which the two ingredients of radial and pitch angle diffusion are represented by a series of competing mechanisms. For radial diffusion these are electric/magnetic field variations and ULF waves; for pitch angle diffusion, these are magnetospheric hiss and whistler waves. Direct heating mechanisms via ULF waves and electron cyclotron heating have been proposed as well. Most of these mechanisms have not been verified experimentally, but do have valid circumstantial evidence for support.

Also of interest are the many studies of radial phase-space density in the inner magnetosphere and the conclusion that there is always an ample source population to supply the observed fluxes; i.e., no external sources are needed. These studies, to be definitive, need to be augmented by observations requiring fewer approximations in the calculation of radial phase-space density.

Problem to be solved during the next 4 years:

What is the relative importance of the various mechanisms responsible for the acceleration of electrons to relativistic energies in the Earth's radiation belts as well as the factors governing the relative intensities of these processes? Why are recurrent high-speed solar wind streams more effective than CMEs in producing intense radiation belts?

Topics:

1) How can we relate the efficiency of the various radial transport and pitch angle scattering processes to solar wind input? Can we parameterize these processes by some function of solar wind speed, density, and IMF field properties?
2) How well can we establish the dynamical phase space density gradients in the inner magnetosphere? Knowledge of the phase space density is the only unambiguous way to establish local versus outside sources.
3) What is the relative importance of internal and external sources to magnetospheric energetic particle populations as a function of particle energy and species? Is there a sufficient source for these electrons in the mid-tail region (L=8-11) and if so, where do these particles come from?
4) Why are recurrent high-speed solar wind streams more effective at pumping up the relativistic electron population in the radiation belts than are the geomagnetic storms that typically occur around solar maximum? What are the physical param-

eters in these streams that make a difference? Is the difference in magnetospheric response partly a case of high geomagnetic activity driving greatly enhanced electron losses?

Approach:

The ISTP spacecraft are well positioned for addressing these topics. The orbit of Polar coupled with the locations of Geotail, SAMPEX, the LANL, GPS and HEO combination, and the addition of Cluster give us an opportunity for detailed examination of the critical regions of geospace for the relativistic electron problem.

In particular, the orbital precession of Polar and its complete particle energy and composition instrumentation have recently and will continue to provide needed information on the near-equatorial plane phase space density from the location of the peak electron fluxes around L=4 out past geosynchronous orbit to L=10. Figure 13 illustrates Polar's coverage of the spatial parameter space of interest. Polar is currently the only mission that measures the internal magnetic field along with the energetic particles of interest. The data can be used to aid in the interpretation of off-equatorial measurements of less sophisticated instrumentation on GPS and HEO spacecraft thereby expanding the range of coverage for phase space density statistical databases. Geotail's complementary mid-tail measurements are of particular interest, as this region is the critical source for radial diffusion mechanisms. The positioning of spacecraft during the declining phase of the solar cycle will provide the opportunity to compare radiation belt enhancement and decay processes as they respond differently to CME/magnetic cloud impact and to recurrent high-speed solar wind streams.

Discussion:

An example of an important shock event occurred on March 24, 1991 when within 90 seconds intense fluxes of electrons and protons were injected into the slot region where SAMPEX observed them persisting for several years, only very slowly dying away. Figure 14 shows a simulation of the 13 MeV relativistic electron flux (lower panel) for this event. The intense fluxes in the normally empty slot region, at L-2.5, are created by an induction electric field, produced by magnetopause compression, which transports electrons inward and energizies them on an electron drift timescale of 1-2 minutes. The simulation uses the LFM 3D

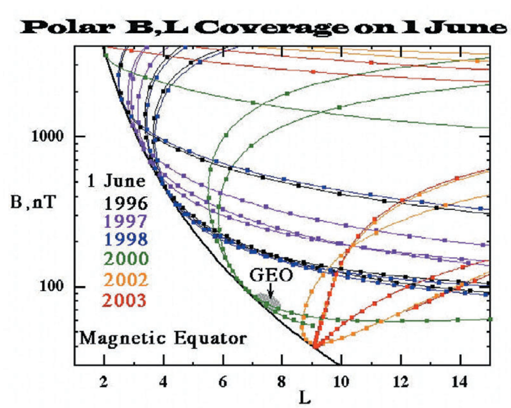


Figure 13. Coverage of B-L parameter space for the Polar spacecraft during the lifetime of the mission. Orbital coverage is shown for one day each year, the parameter space in-between individual lines is gradually filled as each year progresses.

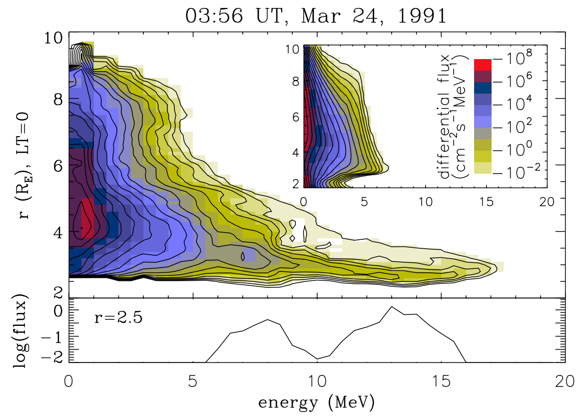


Figure 14. Simulation of the sudden development of relativistic electron enhancements in the L=2.5 slot region during 24 March 1991 CME shock event. This demonstrates the ability of magnetosphere compression and the associated inductive electric fields to accelerate electrons within 1-2 minutes.

global MDH code described in section II-1 to drive guiding-center test particle simulations in the equatorial plane [*Hudson et al.,* 1999; *Elkington et al.,* 2001]. The simulation was initiated with an AE8MIN electron source population as shown in the upper right panel.

Recurrent high-speed solar wind streams associated with coronal holes seem to be more effective than the CMEs associated with solar maximum in producing enduring relativistic electron enhancements in the Earth's radiation belts. This is apparent from the high-speed streams present during the descent from solar maximum around 1994 that were highly effective in producing such electrons. Figure 15 shows the mean dose per orbit caused by electrons with E>1.5 MeV during this period. These measurements were made by an instrument onboard 1994-026, a national security satellite at HEO. Clearly, for 1994-1996, the high-speed streams were statistically the most geoeffective driver of relativistic electron acceleration.

These earlier data sets, while intriguing, are not efficient for studying the underlying physical processes primarily due to poor solar wind parameter coverage (Figure 16) and the lack of com-

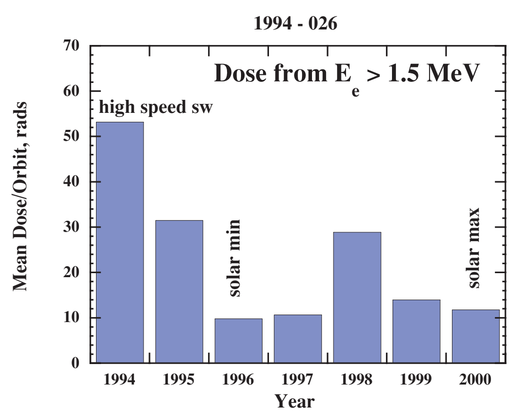


Figure 15. Mean radiation dose per orbit caused by electrons with E>1.5 MeV onboard 1994-026, a military satellite in Molnyia orbit. High-speed solar wind streams present during the descent to solar minimum around 1994 appear to be the most geoeffective driver of relativistic electron acceleration.

plete magnetic and electric field information. ISTP brings full sets of field and particle instrumentation, including full composition, to bear at the right locations and at the right time to address both the internal dynamics and the external sources.

The advancement of good, dynamical models valid during disturbed times of interest will also be important during the next few years. It will be important to identify important physical processes by testing a variety of solar wind input parameters within the models and comparing with the newly acquired multi-satellite data sets. For many processes this might involve a chain of dependencies; for instance, ULF waves play a large role in both direct heating processes and fast recirculation processes and while there is a general association of these waves with fast solar wind speed, the details are not known. An example of modeling work capable of eventually combining larger scale global recirculation mechanisms along with small-scale, fast wave-particle interactions is the global 3D kinetic, convection and diffusion model of *Fok et al.,* [2001]. Figure 17 shows several frames from their simulation of equatorial electron fluxes during the progression of a substorm. Here the convection and inductive electric fields transport plasma sheet electrons, preconditioned during substorm growth, inward to the trapping region creating the freshly injected electron radiation belt. Wave particle interactions can be implemented within their framework as descriptions of corresponding diffusion coefficients. With the unprecedented density of energetic particle instruments available, ISTP has an excellent opportunity to join together with model developers to press toward the predictive capabilities needed for the LWS program.

A more difficult challenge will be to identify the relative importance of internal and external sources to magnetospheric energetic particle populations as a function of particle energy and species. For example, *Fritz et al*. [2000] has made a very controversial proposal for the source of radiation belt energetic ions. MeV particles observed in the Earth's outer cusps have phase space densities equal to or greater than the phase space densities observed in the radiation belts at constant magnetic moment [*Sheldon et al.,* 1998], thus opening up the possibility of diffusive filling of the radiation belts from the cusp. Others have countered that the radiation belts could be the source for the cusp energetic particles. Regardless, the connection, if any, between the two populations will be settled. The ISTP/GGS simulation models and the new Polar orbits are well suited for addressing this problem.

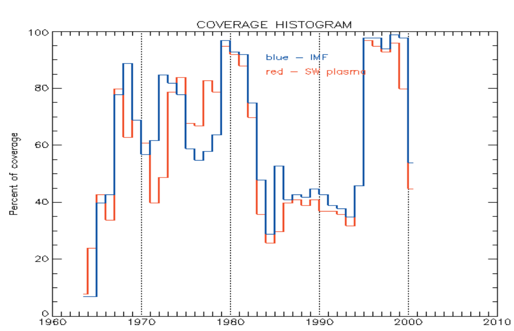


Figure16. Approximate coverage of solar wind plasma and interplanetary magnetic field (IMF) data since 1960. The drop in coverage at year 2000 is an "end of plot" artifact. Note the evolution to almost full coverage at the start of ISTP in 1992.

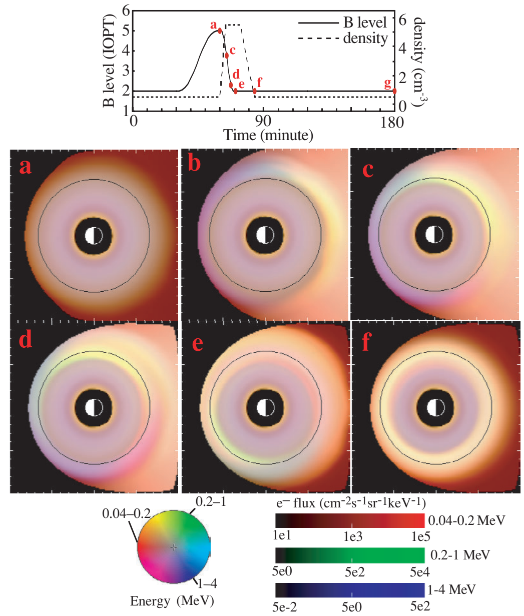


Figure 17. Simulated temporal evolution of MeV equatorial electron fluxes. Electrons with energies 0.04-0.4, 0.4-1 and 1-4 MeV are represented by red, green, and blue colors, respectively. Flux intensity is represented by color brightness. Black circles mark geosynchronous orbit.

Program Element 3: Global Consequences of Magnetic Reconnection

3A. Understand Substorm Onset Processes: the Relevance of Reconnection, Current Disruption and Ballooning Instabilities,

General problem:

The nature and detailed dynamics of magnetospheric substorms that control the flow of energy between the magnetotail and low altitudes remains an area of controversy. There is still work to be done to determine exactly where and how the action starts.

Recent work:

Geotail observations have statistically shown that earthward plasma flows accompanied by northward magnetic fields are predominant earthward of 20 R_E, whereas tailward flows carrying southward magnetic fields are generally observed tailward of 30 R_E [*Nagai et al., 1998*]. These flows are closely associated with auroral brightenings seen in Polar spacecraft images of the Earth's auroral oval [*Ieda et al., 2001*]. These observations support the interpretation that magnetic reconnection between 20 and 30 R_E is an important process converting stored magnetotail magnetic energy into plasma kinetic energy powering substorms and aurorae. However, other measurements suggest a more complex process. For example, the auroral brightenings that are coincident with both the Earthward flows and the tailward moving plasmoids often correspond to smaller "pseudosubstorms" - brightenings at the poleward edge of the auroral zone [*Lyons et al*., 1999] rather than brightenings of the equatorward auroral arc associated with substorm onsets. If the equatorward arc is taken as the footpoint of the substorm onset region, tracing this footpoint back along a magnetic field line locates a very critical region for the onset process. This region is generally thought to be between 5 and 12 R_E where the field configuration changes from dipolar to tail-like and large pressure gradients exist [*Yahnin et al*., 1997, *Frank and Sigwarth,* 2000; *Frank et al.,* 2000; *Erickson et al*., 2000]. This region is well Earthward of the reconnection region from 20-30 R_E.

It has been pointed out that large-amplitude Alfven waves originating in the magnetosphere have sufficient Poynting flux to power the aurora [*Wygant et al*., 2000]. The source of these Alfven waves is not yet identified, but important phase space behaviors of the plasma distribution functions in the plasma sheet have been identified [*Chen et al*., 2000; *Fillingim et al*., 2000; *Parks et al*., 2001]. The distributions include nongyrotropic beams indicating microphysical processes are active during substorm onsets. The power spectrum of the magnetic field variations show substantial power up to the local ion cyclotron and lower hybrid frequencies. These observations, while preliminary, indicate that kinetic processes may be responsible for the genertion of the Alfven and other low frequency waves. Possible candidates for kinetic processes inlude ballooning, current disruption and tearing mode instabilities.

Problem to be solved during the next 4 years:

Determine what physical processes are associated with the initiation of a magnetospheric substorm. Determine the relationship between reconnection processes at 25 R_E and current driven and/or ballooning kinetic instabilities at locations closer to Earth. What determines whether a substorm or a pseudobreakup will occur?

Topics:

1) Definitive determination of the location of the substorm onset region.
2) What energy flows into the ionosphere to trigger a substorm or polar boundary auroral intensification.
3) Determine the importance of reconnection processes, kinetic current disruption, and ballooning instabilities.

Approach:

Beginning in the fall of 2001, the multi-spacecraft configuration of Polar, Geotail, and Cluster (Foldout 2, Figure A), will permit detailed investigations of the substorm onset problem in the plasma sheet. Figure 18 illustrates the orbits of these spacecraft projected on the equatorial plane in September 2001. Geotail near its perigee of ~9 R_E will make magnetotail measurements in the further distances where low latitude auroral discrete structures presumably map to in the magnetosphere. The Polar apogee is near the equatorial region and will make measurement just Earthward of 9 R_E, while Cluster will make occasional north/south cuts through the equatorial plane at 20 R_E near the midnight region. Auroral cameras on the Polar and IMAGE spacecraft will monitor the global state of the magnetosphere and detect substorm onsets while the Los Alamos and GOES spacecraft will detect substorm effects at 6.6 R_E, while FAST will observe near the footpoints of the affected field lines. These measurements will permit us to study and determine where substorms originate. Polar will be in an ideal location to monitor energy flow and determine the source region of the substorm onset processes. It will also provide critical magnetic field data that can be used to model the

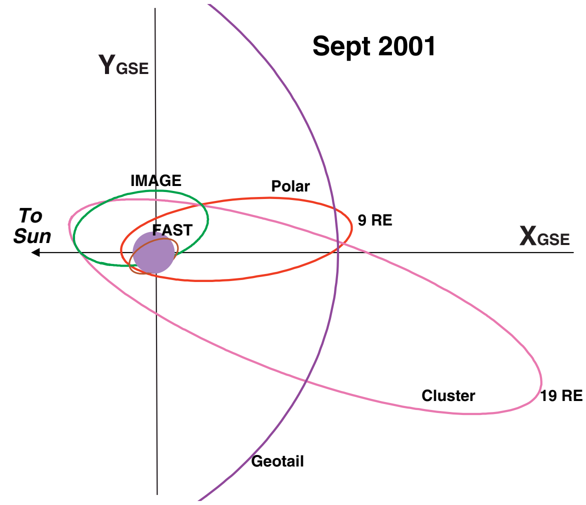


Figure 18. Orbits of Geotail, Polar, FAST, IMAGE and Cluster projected into the equatorial plane in September 2001 when close encounters will help determine the region of substorm onsets.

disturbed field configuration, resulting in a better understanding of how the field maps from the ionosphere to the magnetotail.

Measurements of the distribution function will be used to characterize and formulate substorm physics. The plasma instruments on Polar, Geotail and Cluster will obtain full 3-D distributions of electrons and ions from a few eV to 40 keV. These distributions provide important information on the phase space behavior of the particles. One can examine the dynamic features of the distributions to learn about the source and nature of the particles contributing to both micro- and macro-physical processes. Comparison to bulk parameters and large-amplitude waves will further yield information on the source of the particles that contribute to large velocity moments and wave generation mechanisms

Discussion:

Substorm models can be classified into two categories: one that indicates that the magnetotail energy originating close to Earth flows tailward at substorm onset (ballooning leading to current disruption) and the other where the energy originates in the tail reconnection region and propagates Earthward (merging at the near Earth neutral line). A critical way to differentiate the two mechanisms is to investigate the transition region in the tail where the fields go from tail-like to dipolar and where the plasma pressure gradients are the largest. Figure 19 uses triangles to display the locations of Polar relative to a model field line configuration (top) at the time of substorm onsets during the fall seasons of 1999 and 2000. Yellow and blue shadings indicate the presubstorm plasma sheet and radiation belts, red the post-substorm plasma sheet and magenta the region of substorm injected particles. The bottom portion of the figure illustrates the same spacecraft positions projected to the equator. As the 9 R_E Polar apogee moves equatorward in subsequent years, plasma sheet observations will sweep outward, spending long periods in the likely critical onset region. Geotail and Cluster are expected to supply additional measurements further down the tail during some of these future events. Using interspacecraft timing along with the particle measurements on the various spacecraft to 'gyrosound' the boundaries will help to distinguish between the substorm models.

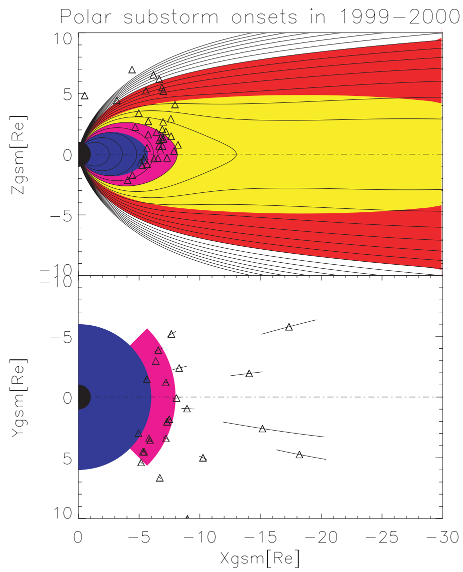


Figure 19. In future years, the locations of Polar substorm onsets for 1999 and 2000 [Toivanen et al, 2001]. As the 9 RE Polar apogee moves equatorward in subsequent years, many new events will be identified within the critical region where the magnetic field changes from dipolar to tail-like. Simultaneous Geotail and Cluster measurements at greater distances will allow study of the propagation of substorm disturbances.

It will also be important during the next 4 years to examine the substorm problem from a kinetic point of view. Much progress has been made with the fluid approximation, but fluid physics has a fundamental limitation — the bulk parameters do not contain the physical mechanism. The examination of merging field lines requires observations on a scale size approaching the ion gyroradius. Current disruption involves microphysical instability processes for which high-resolution distribution function information is needed. The particle detectors on both Geotail, Polar, and Cluster, can produce high resolution distribution functions and they are in ideal position to collect the needed data to identify the instability mechanism that will differentiate between the competing substorm theories. At the same time the 3D Polar electric and magnetic field observations will identify the properties of any low frequency Alfven, ion cyclotron, and lower hybrid wave modes. These instruments will determine the Poynting vector as a measure of energy flow at the time surrounding substorm onset, providing a critical test of onset mechanisms.

Auroral imaging capabilities have always been important to the detailed investigation of substorm timing and progression. The new phase of Polar operations, both the near-equatorial viewing angles and the later ecliptic normal orientations, presents some obstacles while opening up other new imaging opportunities. Polar will be able to perform simultaneous observations of the northern and southern aurora with a single camera (See Figure 2). These can be used to investigate the conjugacy of the auroral oval, particularly in relation to the location and timing of the auroral substorm onsets. The details of complex auroral arc structures can be investigated in coordination with ground-based observatories such as SuperDARN and EISCAT.

3B. Define the Controlling Magnetosheath Reconnection Processes and Sites and Quantify their Relative Importance for System Dynamics

General problem:

The study of magnetic reconnection has been greatly advanced in the past 5-10 years by solar observations (YOHKOH, SOHO), magnetospheric observations (Polar, Geotail), theory/simulations and laboratory experiments.

The process is of fundamental importance to the magnetosphere and to astrophysical plasmas because it converts magnetic energy into kinetic energy and thereby drives dynamical processes. ISTP observations have provided paradigm-breaking evidence that reconnection occurs not only near the sites of anti-parallel fields, but is rather more widespread and guided by principles not completely understood.

Recent work:

The ISTP spacecraft have observed reconnection and made important strides in verifying reconnection predictions throughout geospace with measurements from the flanks of the magnetopause with Geotail [*Phan et al.,* 2000, 2001], in the deep tail with Wind [*Oieroset et al.,* 2000], in the solar wind with Wind [*Farrugia et al., 2001*] and in the magnetosphere cusp layers with Polar [*Scudder et al.,* 2001*; Chandler et al.,* 2000].

Problem to be solved during the next 4 years:

The essence of the problem in providing a physical description of the interaction lies in understanding the large number of magnetic irregularities in the structured solar wind and the ability of the Earth's fields to cope and readjust to the frequent rearrangements of the boundary conditions. The geoactive period associated with the decline of the solar cycle and the well-instrumented fleet of spacecraft of ISTP are best suited to advance this key objective.

Topics:

1) Which of the important reconnection processes and/or sites dominate and under what conditions? Anomalous resistivity versus collisionless conductivity? Sweet-Parker versus Peschek? Driven versus spontaneous? Sub-solar versus high latitude merging? Component versus antiparallel? Merging versus current disruption? Steady versus impulsive?
2) What role does turbulence play at the boundary layers between solar and magnetospheric plasmas?
3) What is the energy/mass transfer budget controlled by reconnection at the magnetopause?

Approach:

Several important problems of interest in this field can be immediately addressed with the combination of Polar, Geotail, Wind, Ace and Cluster covering the global interaction arena (Foldout 2, Figure B). The new subsolar magnetopause skimming orbits of Polar will place the particle and fields assets for long durations in the vicinity of the subsolar reconnection inflow-outflow regions. Skimming orbits poleward of the cusp have been used already on Polar to make superposed epoch pictures of the separator line environment, and to establish the prominent role played by the ambipolar electric field in collisionless reconnection [*Scudder et al*., 2001]. On May 4, 1998 an unusually fast and dense solar wind compressed the magnetosphere so greatly that Polar entered the magnetosheath well before it reached apogee and thus was able to examine the near subsolar magnetopause. This one crossing demonstrated that Polar with its long electric field antennas, 3-D plasma instruments and high-resolution magnetic measurements is ideally suited to study subsolar reconnection in spite of having a single point of observation. The new orbit configuration requires only modest magnetosphere compressions to achieve the same observing opportunities. While Polar makes these north-south cuts across the interaction region, Geotail will make East-West cuts through the same region every 4 days (Figure 20). This, together with ACE monitoring the external circumstances and occasional conjunctions with Cluster in the high latitude cusp and mantle, provide a fabulous opportunity to determine large-scale reconnection dynamics and make the first true estimates of the global influx of solar wind plasmas under the varying and dynamic conditions of solar cycle decline.

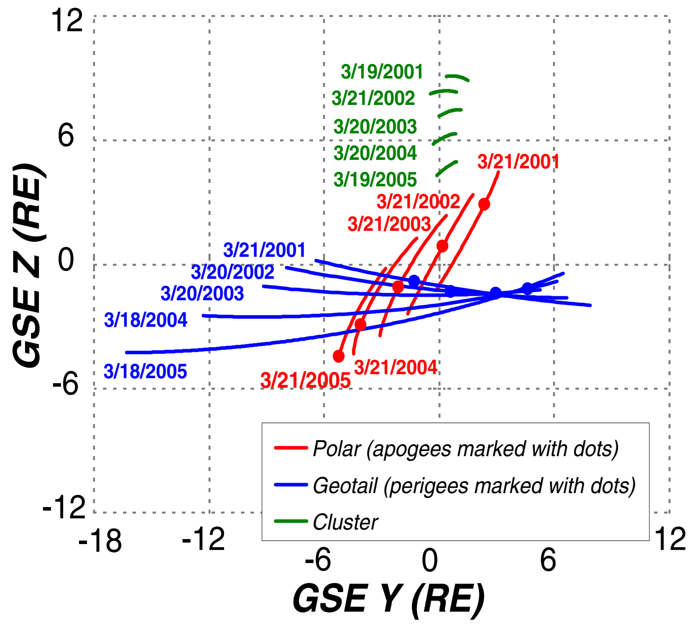


Figure 20. Complementary Polar, Geotail and Cluster orbit configurations for dayside reconnection studies. These spacecraft together with Wind and ACE monitoring the external circumstances determine large-scale reconnection dynamics and make the first true estimates of the global influx of solar wind plasmas under the varying and dynamic conditions of solar cycle decline.

<u>Discussion</u>:

The anti-parallel merging hypothesis has guided expectations about dayside magnetopause reconnection for some time [e.g., *Crooker*, 1975; *Luhmann*, 1984]. However, there are those who believe that while high-latitude reconnection is important, it occurs at a fairly benign place and that significant, if sub-maximal, reconnection rates occur in locales with less than anti-parallel field shear. Among these was the observation of *Chandler et al*. [1999], of low temperature ionospheric ions in the mid-latitude magnetosheath flow during generally northward IMF conditions (Figure 21). The relatively long resident times in the magnetopause entry layers will allow assays of how matter enters as the external geometry switches the preferred site of reconnection.

Quasi-steady reconnection on a boundary surface should be constrained topologically as well as by local magnetic shear. If so, neutral line configurations under varying IMF clock angles for the two reconnection scenarios should be as illustrated in Figure 22. Component reconnection defines a local neutral line along which field lines are reconnected smoothly, i.e., without entanglement with neighbors. When non-uniform fields reconnect on a surface, a locus can be defined as an X-curve across the surface, along which reconnection can proceed. A family of locii can be found by integrating the local neutral line across the surface from arbitrary points. Note that the subsolar point provides a strong candidate point for anchoring a prime locus. Unlike the locus of antiparallel reconnection, the locus of component reconnection can traverse the subsolar magnetopause at any clock angle of the interplanetary magnetic field. It may be that this locus represents the natural location of reconnection on the magnetopause, subject of course to non-uniformities and temporal dynamics of the interplanetary magnetic field and plasma. Conversely, there is some evidence that reconnection can first occur at one cusp followed by reconnection at the opposite hemisphere cusp and that the boundary/entry layers are a byproduct of this sequence of events [*Fuselier et al.,* 2001].

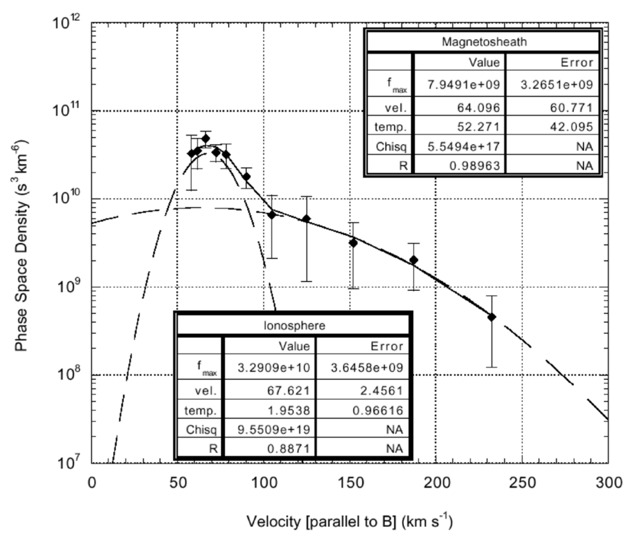


Figure 21. A typical distribution of ions observed in the slowly moving (<100 km/s) magnetosheath at mid latitudes [Chandler et al., 1999]. A population of very low temperature ions is distinct from the bulk magnetosheath population, and indicates cold ionospheric (plasmaspheric) leakage into the lower latitude magnetosheath, presumably at a low latitude reconnection site. Different IMF orientations and merging locations lead to distinctly different plasma populations being observable from a given location.

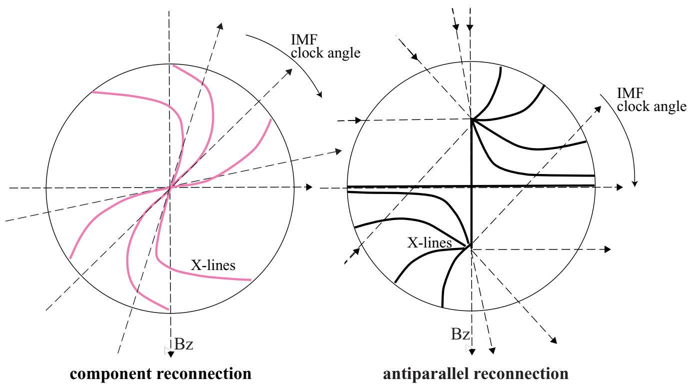


Figure 22. A sketch comparing the qualitative predictions of the antiparallel reconnection hypothesis (black lines) and the component reconnection hypothesis (magenta lines). Component reconnection allows for subsolar merging at all clock angles, with varying extent to high latitudes in response to clock angle

It is clear that only the simplest of Sun-Earth connections result from steady IMF and solar wind boundary conditions. We know there are times when reconnection appears to be nearly quasi-steady, and other times when it appears to be impulsive. We don't know the degree to which it is one or the other, which is critical to understanding reconnection control mechanisms and the degree to which it supplies mass and momentum and thereby controls geospace dynamics. Detailed resolution of the energetic particle spectrum will play an important role in that analysis. The high-speed particles moving along field lines act as a remote sensor of the distant acceleration regions. Detailed measurements of the magnetic and electric fields and the presence or absence of thermal plasmas give the context. High-resolution electron distributions and ion composition measurements are important for getting the stress balance right. The EFI electric field and Hydra electron instruments on Polar have burst mode capabilities to capture the phenomena at the highest possible data capture rate. Such burst modes have been used extensively throughout the cusp auroral zones during earlier phases of ISTP's mission. The new understanding that the magnetic separator is a region of very high electron beta plasma, will allow development of onboard data processing triggers to invoke the burst mode on approach to such layers. This level of measurement resolution will allow ISTP to document the formation and modification of entry layers formed by ejecta from recent, higher-latitude reconnection layers.

New initiatives with regard to reconnection processes will be pursued in the magnetosheath and in the solar wind. It has long been surmised that reconnection could occur in the solar wind, especially at sector boundaries, or across the heliospheric current sheet. There is recent evidence that this process does indeed occur [*Farrugia et al.,* 2001]. Boundary layers, geometrically conducive to reconnection, may be induced to connect more rapidly as their extremities are compressed and differentially refracted into one another at encounters with the curved bowshock.

Recent results of 3-D MHD codes suggest that reconnection between solar wind and magnetosphere flank field lines occurs in the magnetosheath proper [*Maynard et al.,* 2001]. Equator S and Geotail measurements in a skimming orbit along the flanks have documented plasma jetting in opposite directions from a suggested separator line [*Phan et al.,* 1997]. Magnetic discontinuities in the solar wind launch fast, slow, and Alfven model waves when they impinge on the curved bowshock. These daughter waves can be focused in an interfering manner and focusing may lead to field line compression in complicated patterns even as they proceed towards the magnetopause. If and when such interconnection occurs, the complicated patterns should be imposed on the lobes and magnetotail, including effects on rerouted closed magnetic field lines that link down to the auroral region.

Program Element 4: Quantify the 3-D Structure and Evolution of Large-Scale interplanetary Configurations and Their Interaction with the Magnetosphere

4A. The Evolution and Dynamics of Large-Scale Interplanetary Structures: Implications for CMEs, Shocks, and Solar Energetic Particles

General problem:

Understand the structure and evolution of mesoscale interplanetary configurations (0.1-1AU) that influence Solar-Terrestrial connections. The emphasis has been on understanding individual measurements of magnetic clouds and ejecta and their relation to solar phenomena such as CMEs, filaments, and flares.

Problem to be solved during the next 4 years:

Determine and understand the 3-D configurations and evolution of ejecta and the implications for understanding CMEs, shocks, and solar energetic particles.

Topics:

1) CME classification and the consequences of colliding CMEs
2) Shocks and particle acceleration
3) Solar energetic particle acceleration

Approach:

1) Use the newly-configured Wind orbit with SOHO, ACE and Ulysses observations to study the topology of interplanetary structures.
2) Use radio wave observations from Wind, Ulysses and solar observatories to study the propagation and interaction of CME shock fronts. From now until late 2002, the URAP instrument on Ulysses will be making simultaneous observations of CME shocks as the spacecraft returns from the vicinity of Jupiter to make another pass over the Sun's pole. This dual Wind-Ulysses conjunction will allow the two radio instruments to perform full 3-D triangulations of CME-related interplanetary shocks as they approach Earth.
3) Work closely with modelers to test alternative ideas and modeling approaches for predicting the structure and evolution of mesoscale flow configurations.
4) Following the launch of Stereo, now projected for December 2005, use Wind together with STEREO radio measurements to obtain a comprehensive picture of the structure and evolution of transient flows in the solar wind and their relation to Earth.

Discussion:

Are there distinct classes of CMEs and what are the geoeffective consequences of colliding CMEs?

A major question, addressed at the AGU in a special session [*Riley*, 2001], is whether or not there are two distinct classes of CMEs: fast flare-related events and slow prominence-related events. The distinction may rest on precise determinations of the initial degree of acceleration of the CME away from the Sun [*Gopalswamy et al*., 2000]. Wind/WAVES and SOHO/LASCO can make simultaneous radio and white light measurements of CMEs, some of which are now known to become super-Alfvenic only in the outer corona [*Reiner et al*., 2000]. In this way, the precise acceleration profile of some CME shocks can be measured. The solar Type II radio bursts originating from these CME shocks that develop only in the outer corona or in interplanetary space are, in fact, only observable from Wind/Waves. These observations thus provide unique information regarding potentially geoeffective shocks from oncoming CMEs.

Close examination of simultaneous LASCO white light and WAVES radio measurements made in this region recently led to the discovery of colliding CMEs (see discussion in Section IV, ISTP Accomplishments) and CME merging in which the trajectories, topology, and speeds of colliding fronts are significantly altered [*Gopalswamy et al*., 2001]. Combined WAVES/LASCO observations of colliding CMEs in the upper corona should make important progress in answering the specific question of the effect on space weather of colliding CMEs.

What is the mechanism that accounts for solar energetic particle acceleration?

Most researchers believe that the energetic particles in gradual SEP events are shock accelerated, but there is little agreement on many of the details. For example, the relationship between CME shock speed/spatial scale and particle acceleration energy/flux is not understood. Also, there are now known from measurements by Wind/EPACT to be dramatic abundance variations with time in large CME-driven events [*Reames*, 1999]. Part of the problem is due to the fact that interplanetary shocks are not spatially or temporally uniform. Better definition of CME-related shock structures, both from the 3-point Wind, ACE, and Geotail measurements, and from the 3D Wind-Ulysses radio tracking of oncoming shocks, will provide much-needed input to shock acceleration models for SEPs.

In addition, important distinctions between gradual SEP events and flare-accelerated events with respect to spectra, abundances and ionization states still need to be made [*Reames et al*., 2001]. Beginning later this year it will become possible for the first time to compare abundances measured in situ by EPACT with remote determinations of abundances at impulsive solar flare sites inferred from gamma-ray line observations by the new HESSI mission [*Lin*, 2000]. Such measurements should shed light on the issue of resonant wave-particle interactions in flares in general [*Reames*, 2000].

Shocks and particle acceleration

The study of collisionless shocks as particle accelerators is not only important on interplanetary scale lengths as described above, but it is also important on the microscale. A complete and adequate theoretical treatment of the acceleration of electrons at shocks is not available, thus additional high-quality measurements of foreward and reverse shocks over a wide parameter regime remain essential. The Wind spacecraft is well equipped to make the relevant measurements. For example, ion observations with the SWE Faraday cup in the anti-sun direction show ion fluxes to be present after the passage of shocks, similar to those described by *Ogilvie et al.* [1993]. The acceleration of solar wind ions is much less efficient than the acceleration of pick-up ions at shocks [*Gloeckler*, 1999], but the low intensity of pick-up ions near 1AU allows the solar wind ions to be seen.

4B. Extrapolate Upstream Solar Wind Conditions to the Magnetosphere

General problem:

Knowledge of the state of the solar wind immediately upstream of Earth's magnetosphere is essential. However, the precise topology of moderate to large-scale interplanetary structures is not known, preventing accurate projection of solar wind conditions from spacecraft that are not near the bow shock.

Recent work:

Multi-spacecraft measurements in the solar wind have been made almost exclusively along the Earth-Sun line, with very little baseline in the Y_{GSE} direction. The new Wind orbits will remedy this deficiency.

Problem to be solved during the next 4 years:

Determine and understand the 3-D structure of meso to large scale (20-200 R_E) interplanetary solar wind structures. This will enable more reliable extrapolations from remote measurement points to the magnetosphere and provide more accurate input to geospace models and simulation boundary conditions. Such observations will also help solve fundamental science problems regarding the nature of the solar wind, for example solar wind turbulence.

Topics:

1) The large-scale morphology of solar wind structures
2) The structure of solar wind MHD turbulence
3) The relationship between solar wind structures and their solar sources and geoffectiveness

Approach:

1) With the 3-D Plasma instrument, Wind is the only spacecraft capable of detecting electrons in the 1-40 keV energy range. Such measurements are essential for probing interplanetary magnetic field structures, their connectivity to the corona, and topological changes resulting from disconnection from the solar surface [*Larson et al*., 1996]. This work is especially relevant to the analysis of bi-directional streaming events within magnetic clouds.
2) Use simultaneous multi-spacecraft observations parallel and normal to the Earth-Sun line upstream to make definitive determinations of the 3-D structure of the mesoscale objects.
3) Work closely with modelers to develop clear predictions of 3-D microstructure of turbulence, flow boundaries, and magnetic holes for alternative physical models.
4) Determine which models are consistent with the observations.

Discussion:

What is the large scale topology of solar wind structures observed at 1AU?

Foldout 2, Figure G and Figure 23 show a typical example of one of the new spacecraft configurations that will occur between ACE (near L1), Wind (near apogee in its DPO orbit), and Geotail in the solar wind near Earth. Such conjunctions, only made possible by Wind's wide-ranging orbit, will provide many opportunities to determine coherence lengths and geometries associated with large-scale interplanetary structures.

Preliminary results [*Collier et al.*, 2000] suggest that some IMF structures have scale lengths of about 20-100 R_E, so that the orbit geometry shown in Figure 23 is entirely appropriate for such investigations. The topologies of structures such as interplanetary reconnection layers, interplanetary shocks, magnetic clouds and flux ropes [*Moldwin et al.*, 2000], the heliospheric current sheet [*Szabo et al.*, 1999], planar magnetic structures, anomalous low-density structures [*Usmanov et al.*, 2000], and shocks internal to magnetic clouds [*Collier et al.*, 2001] will be investigated for the first time on spatial scales appropriate to the medium. Improved knowledge of the structure of such important solar wind features will greatly improve the accuracy of solar wind parameters that are extrapolated, or projected, from remote measurement sites, such as from ACE or Wind.

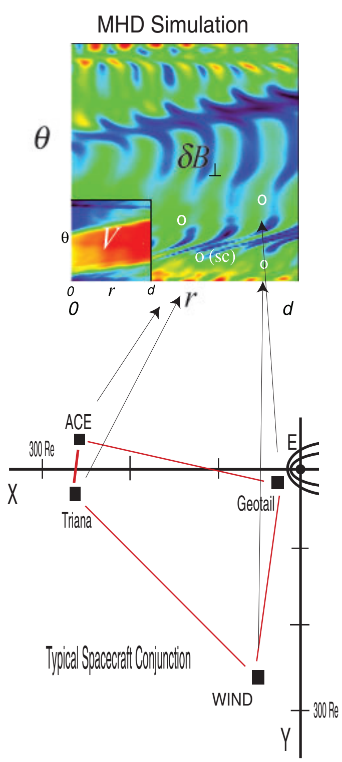


Fig 23. Interplanetary turbulence contours [Goldstein et al., 1999] illustrating how multi-spacecraft measurements will be applied to models on interplanetary scale lengths. Arrows point to the relative locations in the ecliptic plane of the four spacecraft superposed onto the turbulence model.

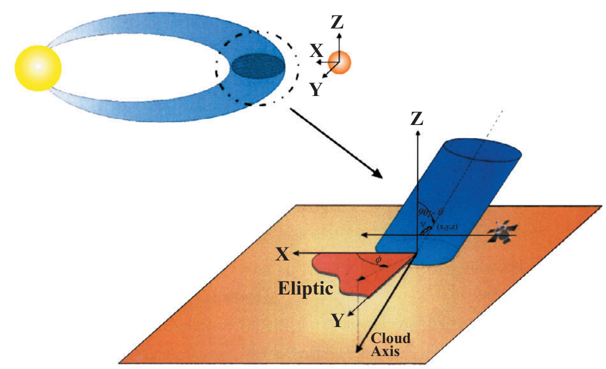


Figure 24. Force-free model of a magnetic cloud [Hidalgo et al., 1999] showing coordinate system and typical single-point measurements through cylindrical cloud.

What is the structure of solar wind MHD turbulence?

By way of a specific example we show an application to a solar wind turbulence model in Figure 23. What is seen in the solar wind at 1AU is a complex mixture of convective distortions in the plasma due to inhomogeneities of flow and propagation speeds. The multi-spacecraft, mesoscale measurements proposed here will provide the only means to directly measure the wave vectors of solar wind variations and thus understand the geometry of particular structures. Shear in the background flow may determine the shape of large-scale fronts, for example. The MHD simulation of Figure 23 illustrates a planar front distorted by a fast microstream flow (insert in red) leading to tilted structures in delta B. Besides being of fundamental importance to solar wind physics, the measurements will have direct application to predicting solar wind input to the magnetosphere.

How do interplanetary structures seen at 1AU relate to solar impulsive events and their geoeffectiveness?

Using information gained from multi-scale analysis of the solar wind, investigators will determine how large-scale solar wind structures relate to solar impulsive events and their geoeffectiveness. For example, present models of magnetic clouds are based on rather meager observational evidence. The structure of magnetic clouds [e.g., *Hidalgo et al.*, 1999] gained from widely-spaced, 2D, multi-spacecraft observations, will lead to a more generally satisfactory global theory of these large interplanetary features, which can be used to better map them back to the corona. An example of a force-free cloud model, shown in Figure 24 is well adapted to modification by comparison with observations by widely-separated spacecraft such as Wind, ACE, and Ulysses. The new Wind orbits, which take the spacecraft as much as 350 R_E from Earth perpendicular to the Sun-Earth line, are particularly well-suited for this purpose. Better knowledge of the topology of these events should have a profound effect on our understanding of their interaction with Earth's magnetosphere.

C. ISTP Program Benefits to the OSS Science Community

ISTP Science as a Community Resource

The full set of GGS missions has been in place for five years and, as a result, the ISTP/GGS investigators have been able to make significant impact on the space physics literature. Special journal issues and special meeting sessions are regularly sponsored by ISTP/GGS. These are in addition to the semiannual ISTP workshops. There have been over 985 refereed publications featuring ISTP/GGS science in a primary role; over 267 with Wind data; over 368 featuring Polar data; and over 350 with Geotail participation. In addition, several instruments regularly provide data in a secondary role; for example, the Wind and Geotail solar wind IMF and solar wind plasma data. If these statistics were to be included as well, the ISTP/GGS participation rate would exceed 50 percent of all refereed JGR and GRL blue magnetosphere science publications. The value of the ISTP program is well demonstrated by the widespread presence of ISTP/GGS science, in some form, at every space physics meeting and in every AGU space physics journal.

The Mission Investigators

ISTP/GGS investigators have accepted support responsibilities over and above their mission obligations. Wind and Geotail are important solar wind monitors; their investigators maintain timely service of calibrated IMF and solar wind plasma parameters (http://cdaweb.gsfc.nasa.gov/). The Polar imagers provide definitive information on the timing of substorm phases and are regularly called upon to provide media-ready descriptions of the magnetospheric response to solar events. The ISTP/GGS project office supports a system of declaring “special events,” and coordinates the collection of solar, magnetosphere, and ground based data on one WWW site (http://www-istp.gsfc.nasa.gov/istp/events). This activity reduces the time individual researchers spend on data gathering and data synchronizing activities, increasing productivity. Several of these special services call for investigators to respond, mostly uncompensated, outside of normal working hours. The space physics community as a whole has always been appreciative of these efforts.

The ISTP/GGSData System as a Community Resource

Because ISTP/GGS is meant to integrate the solar, magnetosphere and ionosphere science communities, the ISTP ground data system implemented several procedures intended to serve the wider research community. The ground system supports data distribution on CD-ROMs in CDF format, and the WWW distribution of text, CDF and graphical forms of processed data for several missions in addition to Wind, Polar, SOHO, and Geotail. IMP-8, CANOPUS, SuperDARN, Sonderstromfjord, SESAME, Equator-S, GOES, LANL, FAST, SAMPEX, Interball, ACE, Cluster, and IMAGE key parameter data are all collected and distributed through the ISTP Central Data Handling Facility. Ancillary computations provide definitive and predictive spacecraft positions in magnetic coordinates and calculate physical regions of interest (i.e., cusp or plasmasphere). Solar and magnetospheric event sequences are monitored and organized lists made available. The ISTP Central Data Handling Facility in combination with the NSSDC data archiving are OSS’s “one-stop shopping” for space physics data. These are supported, as much as is possible within budget considerations, over and above the normal service of data products to the ISTP/GGS mission principal investigators. Given the resources, the ISTP CDHF would like to take additional steps toward serving the wider space physics community. See the separate *International Solar-Terrestrial Physics Stanley Shawhan Central Data Handling Facility* proposal for a more complete description.

Technology Transfer

Future technology transfer is anticipated primarily in the area of improving the coordinated collection and distribution of multi-satellite data sets and in new efforts to facilitate the translation of that data into science results. These efforts are of immediate importance to the upcoming multi-satellite missions of Magnetosphere Multiscale, the Living with a Star missions, and Magnetosphere Constellation.

In Summary

As we transition to the next phase of ISTP/GGS we have in place an enormously capable one-of-a-kind system beneficial to all researchers performing SEC system science. The system consists of a fleet of spacecraft, coordinating ground-station instrumentation, theory and simulation elements, and a reliable ground-system to provide processed data products and analysis tools. This extensive dataset, in conjunction with the theory and simulations, provide a much more detailed understanding of the physical processes being studied and will enable SEC to transition to the Solar Terrestrial Probes and the Living With a Star Programs.

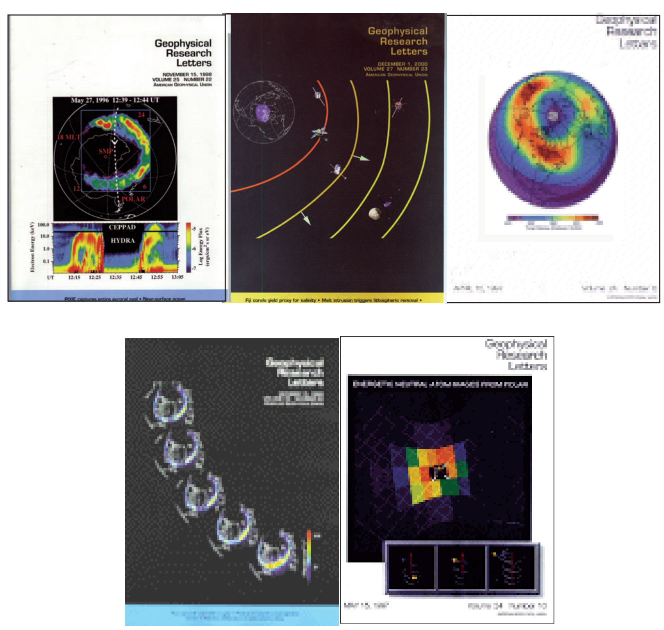


Figure 25. ISTP/GGS regularly sponsors special journal issues and special meeting sessions to ensure ISTP science reaches the widest audience possible.

III. ISTP and the OSS Strategic Plan

Value to the Science Themes

The ISTP/GGS program has been a fundamental component of NASA's Sun-Earth Connection program for many years. It has direct impact on two of the three quests discussed in the Sun-Earth Connection Roadmap, Strategic Planning for the Years 2000-2020. These are:

- How do the Earth and the planets respond? (to the Sun)
- What are the implications for humanity?

Under each of the quests there are several scientific themes.

Under the quest dealing with "How do the Earth and Planets Respond to the Sun," GGS makes substantial contributions to all of the themes. Specifically, our Program Element 1, "Extend the systems-science approach to geospace characterization," deals directly with the Nature of Solar Interactions with the Earth's Atmosphere and Space Environment through its focus on end-to-end understanding of the solar-driven magnetosphere. GGS also addresses the theme of Comparative Space Environments through its quantitative descriptions of the Earth's magnetosphere under the dynamic conditions of the declining solar cycle. Because reconnection is a fundamental physical process that occurs throughout the solar system, our Program Element 3, "Establish which are the controlling reconnection processes and quantify their relative importance for system dynamics," lends itself directly to understanding this process at other planetary magnetospheres. Finally, since GGS directly measures energy deposition into the atmosphere and describes via physics-based models this pathway through which changes in the upper atmosphere are effected, the quantitative descriptions offered by GGS relate to the Impacts on Life on Earth, the final theme under this quest.

Under the second Quest, "What are the Implications for Humanity," GGS makes major contributions to the theme dealing with the *Impacts of Space Weather* by providing quantitative multiscale understanding of the nature of magnetosphere-ionosphere-atmosphere interactions. Our Program Element 2, "Understand dynamic processes associated with the equatorial transition region," and Program Element 4, "Quantify the 3-D structure and evolution of large-scale interplanetary configurations and their interaction with the magnetosphere," feeds directly into models to predict Space Weather. GGS also addresses the theme of *Changes in the Earth's Atmosphere* since the auroral, radiation belt, and atmosphere energy deposition science provides key elements for understanding the ionizing radiation and heating for the Earth's upper atmosphere with major implications for satellite drag. Finally, the theme dealing with the "Habitability of Space" is directly touched upon by GGS detailed characterizations of energetic particle dynamics owing to changes in the solar input.

Relationship to Past, Current, and Future Missions

ISTP/GGS research typically embraces the contributions of several specialized missions outside the ISTP umbrella. Observations from ACE, IMP-8, FAST, SAMPEX, Ulysses, and IMAGE, plus the LANL and GOES geosynchronous spacecraft and non-GGS ground-based facilities are all regularly correlated and combined with GGS observations. These spacecraft and facilities are highly complementary to the GGS science goals. The ISTP ground data system, described in a separate proposal, has accepted responsibility as the primary distributor of processed key parameter data for many of these missions. This was done as part of ISTP's philosophy of being the community resource of easily accessible data representative of the entire Sun-Earth connected system for the study of the wide variety of solar input conditions.

Because ISTP was the first NASA effort at studying the system wide impact of the Sun on the near Earth' environment, ISTP acts as a technology pathfinder and scientific complement for the Living with a Star initiative. The integrated flight operations facility, the central data handling facility, and the tightly coupled theory, modeling and ground-based components of ISTP can be identified as testbed technologies for enabling a successful Living with a Star program.

Several science objectives pursued by GGS provide operational paths for the upcoming Magnetosphere Multiscale (MMS) mission. MMS is aimed at the microscale and mesoscale processes of energy transfer within and into the magnetosphere, especially with regard to reconnection. GGS' substantial contributions in the realms of dayside magnetopause and tailward NENL reconnection processes provide the macroscale workings of these processes and thereby point to fruitful areas of research to be pursued by MMS.

Wind in the Stereo and LWS Era

The varying Wind orbits have been implemented as efficiently as possible in order to conserve onboard fuel. As a consequence, Wind retains sufficient fuel to return to the L1 halo orbit or to the dayside double-lunar swingby (DLS) orbit in order to serve as the full-time upstream solar wind monitor should the ACE spacecraft fail.

Wind's function as an upstream monitor becomes even more important post 2005 in the LWS era when depleted fuel supplies on ACE will begin to compromise its solar wind monitoring capability. Should Wind remain healthy until that time, and there is every indication that it will, it may be the only spacecraft available to function in the critical role as a solar wind monitor upstream of Earth.

Polar's Role in the Magnetosphere Imaging Era

Polar provides invaluable and irreplaceable science support for ongoing and future magnetosphere imaging missions. The IMAGE and TWINS missions have assumed there will be in situ measurements of the inner magnetosphere to support their remote sensing and global ENA imaging observations. As explained earlier, Polar observations along a path through the images establishes the baseline for image inversion. Polar will play a similar role for the TWINS mission. Although TWINS will provide "stereoscopic" ENA views of the inner regions, the analysis will still require "ground truth" measurements from Polar to confirm reliability.

IV. What have we learned from the explorations of ISTP?

The Goal of ISTP is:

"To develop a comprehensive, global understanding of the generation and flow of energy from the Sun through the Earth's space environment (geospace) and to define the cause-and-effect relationships between the physical processes that link different regions of this dynamic environment." – Alexander and Nishida, 1984

GGS, together with its many collaborating space-based, ground-based and theoretical studies, has fulfilled most of the primary ISTP science objectives. The successful observational campaign has given us a rich long-term database. Herein we present an overview of some of the important discoveries made during the first stage of ISTP's initial operations and provide context for the science to be achieved during the continuing mission. We organize the discussion according to the science topics proposed for the GGS/SOLARMAX phase of the mission.

Coronal and Interplanetary Shocks

The source of the driver behind particular eruptive shocks has been a long-standing controversy – candidates being CMEs, flare blast waves, reconnection jets, etc. While interplanetary (IP) shocks are definitely associated with CMEs, the source of coronal shocks, and their relationship to IP shocks, is still not completely clear. Solar Type II radio bursts, which are produced by fast-mode MHD shocks, are the principal radio frequency evidence of shock-associated solar eruptive events. Recent evidence based on the radio window opened by Wind/WAVES points to there being very little correspondence between coronal and interplanetary shocks, except in the case of large-scale CMEs [*Gopalswamy et al*., 2001; *Reiner et al*., 2001]. Thus, while IP shocks often have an identifiable CME driver, coronal (metric) Type II bursts, and hence coronal shocks, probably have another source. In fact, based on the starting frequency and timing of metric bursts, *Vrsnak* [2001] has concluded that coronal shocks are most likely driven by the blast waves generated by flares. This dichotomy is crucial, first, if we are to understand the formation of shocks in the corona and in interplanetary space, and second if we are to understand the space weather implications of remotely-sensed shocks from solar eruptive events.

Evolution of Large CMEs and Associated Shocks

During solar maximum, CMEs are sometimes expelled in quick succession making the likelihood of a fast CME colliding with previously-expelled slower moving ejecta much more probable. The consequences, both in interplanetary space and for the effect on geospace, are being investigated now for the first time. The first simultaneous white light (LASCO) and radio (Wind/WAVES) detection of such an event occurred in January, 2001; the LASCO image is shown here in Figure 26. Using the radio tracking facility of Waves, Wind scientists [*Gopalswamy et al.*, 2001] were able to track the collision in the outer corona at the same time it was observed visually by LASCO. The simultaneous measurement of such events by two independent instruments makes determinations of the initial acceleration of CME-driven shocks near the Sun a real possibility for the first time [*Gopalswamy et al.*, 2000].

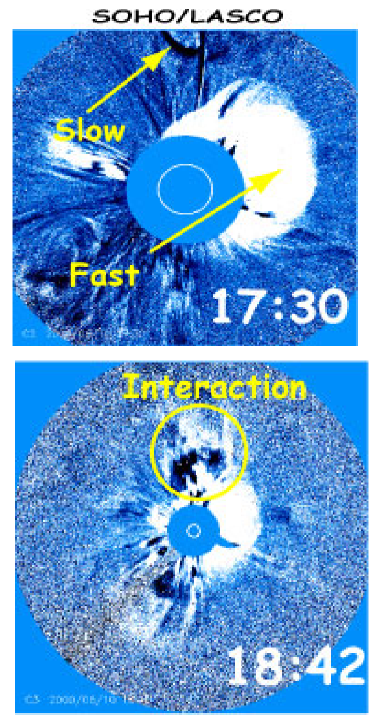


Figure 26. SOHO/Lasco white light Image of colliding CMEs, simultaneously recorded at radio wavelengths by Wind/Waves.

Using the Wind/WAVES radio observations of Type II emissions from CME shocks, *Gopalswamy et al*. [2001] have shown that the interaction between colliding CMEs leads to significant redirection and merging of the shock fronts which may account for some of the false alarms issued for Earth-directed halo CMEs. This discovery has significant space-weather implications. The dual-shock interaction region generates a continuum-like radio emission never before seen. Retrospective analysis has revealed that a significant fraction of the CME shocks formed during solar maximum are involved in collisions.

CMEs, Flares, and Solar Energetic Particle Events

Interplanetary magnetic clouds (MCs), observed at Earth, are an often-seen manifestation of major solar eruptive events. MCs are important not only as large-scale interplanetary structures that can drive interplanetary shocks and have significant impact on geospace, but also because their unusual topology provides a direct probe of impulsive flare sites on the Sun. Wind/EPACT and Wind/3DP measurements of energetic ions and electrons within MCs have shown that impulsive solar flares are the source of significant ion fluxes [*Mazur et al*., 1998]. The association of ions with streaming 100 keV electrons [*Reames*, 1990] established that the particle source is at the Sun and that the particle propagation is along magnetic field lines that directly connect the observer to the flare site [*Larson et al*., 1997]. The flare-accelerated particles have a unique composition compared to the solar corona. They are considerably enriched in ^{3}He (x10^3–10^4), Ne-S (x3) and Fe (x10). There is also the more recent discovery by EPACT of a 1000-fold enhancement of rare, very heavy ($50 < Z < 82$) ions in impulsive SEP events [*Reames*, 2000a]. Consistent with this picture of direct connection to the flare site, *Reames* [1996] showed that the observer's field line must be within about 30° of the flare site to detect the escaping electrons and ions. Two important implications of these observations are that 1) MCs are not closed structures, completely cut off from the solar launch site, but rather they are often magnetically connected to a flaring region at the Sun, and 2) careful ion abundance and composition measurements made within MCs can provide unique information regarding impulsive-flare ions during solar active periods. Such measurements are dependent on the high sensitivity and low energy threshold of the EPACT instrument.

Extreme Events at Solar Maximum

A most important technical accomplishment of ISTP is the tracking of transient events from their birth on the Sun, tracing them through the interplanetary medium, and quantifying their geoeffectiveness in producing magnetic storms, accelerating magnetospheric plasmas, and depositing energy into the atmosphere. The ISTP program has brought the space physics community into an era in which we examine the relationship between solar activity and the various geospace responses as a global system. The propagation of impulsive solar events are routinely followed through the entire system. The individual parts of the closely coupled, highly time dependent system are now systematically studied to see their response to the global disturbance.

Table 5 lists the major geoeffective solar events that ISTP/GGS investigators have studied extensively. The many studies that came out of each event have formed our current, more complete understanding of the magnetospheric interaction with the Sun during solar minimum and solar maximum. That understanding came about one breakthrough at a time, one event at a time.

Jan 7-12, 1997

For the first time, space physicists tracked a solar eruption, from the CME expelled from the Sun, through interplanetary space, until it encountered the Earth's magnetosphere, causing violent disturbances and spectacular aurora. Chromospheric material was observed by Wind, at a time when the density rose above 150/cc. This provided a diagnostic of the chromosphere at a particularly interesting time. Similar events during the declining portion of the solar cycle will provide additional observations for determining the method by which ions in low charge state reach Earth.

The most notable achievement connected with this event was the introduction of end-to-end global MHD simulations to predict, and later to better understand, magnetospheric response. The simulation of the event was a computational coup-de-force that covered 42 hours of real time, and produced over 6GB of data. [*Goodrich et al.,* 1998]. Figure 27 shows one frame from this simulation. The full sequence, which can be accessed at http://www.spp.astro.umd.edu/Research/Mhd/mhd.htm, shows the evolution of field aligned currents and plasma flows. There was good agreement with Polar spacecraft observations. The Space and Plasma Physics (SPP) group at the University of Maryland, who performed this analysis, used the LFM (Lyon-Fedder-Mobarry) 3D, global, dynamic MHD model interactively coupled to a 2D electrostatic, height-integrated ionosphere [*Wiltberger*, 1998]. The results of these efforts are now reaching a larger audience as the simulations are featured in a sequence of the IMAX movie *Solar Max*.

Table 5: Important Geoeffective Solar Events Studied by ISTP/GGS

Dates	Interest
Mar 27 – Apr 2, 2001	2 full halo CMEs , large SEP event , -390 Dst , largest flare (X20) ever recorded
July 14-16, 2000	X-Class flares and fast moving Earth-directed CME. Aurora reached as far south as Georgia and Great Britain.
June 6-9, 2000	Large flares and a high speed halo CME, first coordinated studies with IMAGE, Wind's discovery of colliding CMEs
April 4-7, 2000	Large event causing the aurora to be visible as far south as the Carolinas.
January 27, 2000	Unusual Corotating Interactive Region (CIR)
May 10-12, 1999	Extended interval of low density solar wind, and a more dipolar-shape magnetosphere
Sept 24-25, 1998	WIND/WAVES detected type II and III radio signatures associated with an M6.9 flare. At Earth Dst reached -222 nT and Kp reached 9.
Aug 24-28, 1998	X1 Solar Flare, resulting CMEs reached Earth in only 33 hours, giving a transit speed of ~1300 km/s.
May 4- 5, 1998	Multiple CMEs with last accompanied by X1 proton flare. At Earth, Kp reached 9
April 7-11, 1997	A flare led to a shock wave that led to a CME. The auroral fireworks extended all the way to Boston.
Mar 27 - Apr 2, 1997	Polar confirms the existence of a new type of comet tail on Hale-Bopp
Jan 7-12, 1997	For the first time, space physicists follow a storm from its origin as a coronal mass ejection to a "one-two punch" of Earth that pushes the magnetosphere inside geosynchronous orbit.
May 27-29, 1996	Extended period of geoeffective activity that put the Polar spacecraft within the dayside reconnection layers for an extended interval.

For complete list see *http://www-istp.gsfc.nasa.gov/istp/events/*

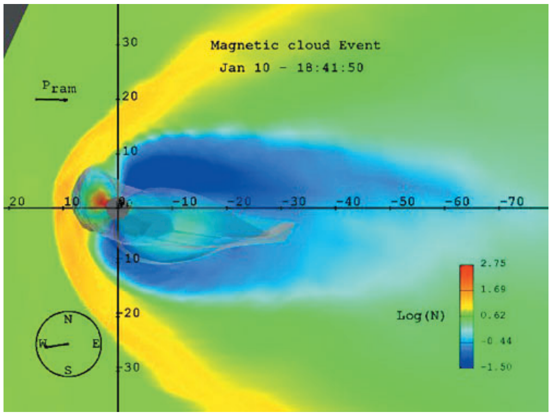


Figure 27. Frame from a 3D MHD simulation of the January 1997 CME interaction with the magnetosphere. The background of the frame shows the log of the plasma density on a noon-midnight cutplane and the grey transparent isosurface represents the last closed field line surface. The full animation shows the flow of mass within the magnetosphere as well as the motion of the last closed field lines.

The development of these simulation sequences is a major milestone for Sun-Earth Connection physics requiring significant science and computational breakthroughs.The end-to-end simulations have become an integral part of the process to understand each variation in the magnetosphere response to solar events. As solar cycle 23 begins its declining phase later this year, we look forward to the opportunity to study the new variety of phenomena associated with recurrent geomagnetic storms.

May 4- 5, 1998 and Sept 24-25, 1998

With the May and September, 1998 magnetic cloud encounters, ISTP/GGS investigators were able to separate the very different response of the magnetosphere to intense solar wind pressure increases as compared to the magnetosphere response from extremes in the IMF direction.

The Wind, Polar and Geotail spacecraft have provided excellent diagnostics of the process of magnetospheric compression. A rapid shock-like compression shrinks the magnetosphere in size, increasing the overall magnetic field strength and rapidly moving plasma downstream along the affected field lines [*Russell et al.*, 1998]. Increased plasma pressure down the throat of the cusp increases its width in local time and latitude [*Zhou et al.,* 2000]. The compressions move past the magnetosphere over a period of about five minutes. The dayside equatorial region experiences an abrupt change in magnetic field strength due to the relatively slow speed with which compressional events advance ahead of the continuing solar wind disturbance. Surprisingly, due to competing magnetopause and tail current effects, the evening sector may experience almost no immediate change in magnetic field configuration while in a region off the equator near the noon-midnight meridian, the magnetic field strength drops when the magnetosphere is compressed. This almost paradoxical behavior was first seen by *Rufenach et al.,* [1992] and *Winglee and Sibeck* [1997] and has now been explained with the aid of the ISTP observations and associated modeling analysis. This may have important consequences for determining how the timing and location of instability regions change under varying dynamic conditions.

As expected, the aurora responds dramatically to interplanetary shock encounters. Enhanced dayside brightenings occur near noon within 2 minutes of the time of pressure pulse arrival and decays away in about 20 minutes [*Zhou et al.,* 1999*; Tsurutani,* 1999]. Unexpected were the spatial and temporal complexities in the auroral forms were imaged [*Spann et al*., 1998]. Auroral activity was recorded over most of the polar cap with significantly more energy precipitated on the nightside, though the most significant impact on the magnetosphere presumably occurred along the dayside magnetopause.

This event produced an immediate, intense ionospheric mass ejection with the mass flux from the Earth to northern lobe altitudes increasing by more than two orders of magnitude [*Moore et al.,* 1999]. This, combined with observations from 1981, indicate that the fluctuations in solar wind pressure control the outflow of heavy ions from the ionosphere (Figure 28). The IMF more directly controls the subsequent dispersal of that flow across polar cap latitudes by controlling transport processes. Solar wind pressure driven ionosphere mass ejections are consistent with strong bulk heating at ionospheric altitudes perhaps through the Poynting flux associated with the enhanced dayside field-aligned current systems. The result is a cloud of dense, relatively cold plasma delivered through the magnetospheric lobes to the near-Earth plasma sheet, where it is expected to impact dynamic behavior related to substorms and storms [*Moore et al*., 2000].

Surprisingly, field aligned and region 1 currents connecting the ionosphere to the magnetopause have little reaction to pressure pulse passages, but are strongly enhanced during southward orientations of IMF [*Le et al.,* 1998]. This finding emphasizes the importance of reconnection as a driver for certain internal dynamics over the contribution due to viscous drag. Dynamic solar wind pressure changes also appear to play, at most, a small role in affecting the ring current system. Rather, the currents are most responsive to IMF direction. It has long been thought that the auroral zone current systems are linked to the buildup of the ring

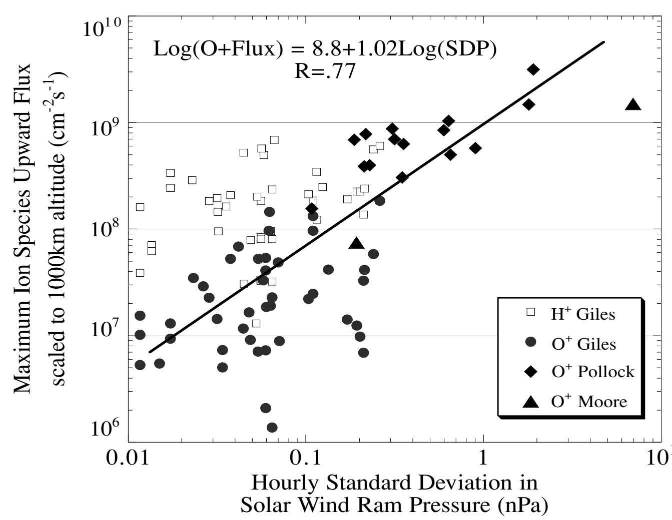


Figure 28. Upward ion flux versus the variation in solar wind ram pressure. With the tracking of CMEs, investigators are able to separate processes responding to impulsive events as compared to those responding to extremes in the IMF.

current during storms in a manner similar to their relation during substorms. The September 24/25 interval was particularly instructive in this respect because it contains a variety of solar wind inputs that excite the auroral electrojet by a similar amount, but there is only one period when the IMF was southward, during which the ring current develops. These types of analysis efforts applied to great storms expected during solar cycle decline will further separate the specific elements of geospace dynamics responsive to one type of solar input or another.

May 10-12, 1999: Anomalous low density solar wind and its geomagnetic consequences

Although not a "great magnetic storm," this was nevertheless a "great event," the study of which had important consequences for understanding the direct connectivity between the Sun and the Earth. For approximately 36 hours starting late on May 10, 1999, the density of the solar wind measured by Wind dropped to a fraction (2-13 percent) of its normal value. The minimum measured density of 0.18 cm^{-3} corresponded to a solar wind kinetic pressure less than 10 percent of its nominal value and a subsolar magnetopause position twice its normal value. The resulting magnetosonic Mach number approached a value of one, resulting in an extremely weak bow shock that expanded as far as 50 R_E upstream of its nominal position [*Fairfield et al.*, 2001]. This event, called "The Day The Solar Wind Disappeared," allowed Polar scientists the opportunity to observe inner magnetosphere plasma processes in the near-absence of a solar wind and identify those processes that act independently of external dynamics. The event presented a challenge to the MHD models because of the low Alfven speed and the expansion of the bow shock past the normal front boundary of the simulation domain. A comparison between the expanded magnetosphere and the compresses magnetosphere can be seen in the simluation results from LFM shown in Figure 29.

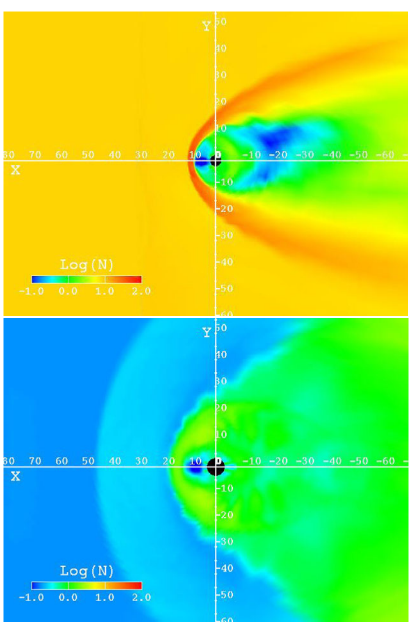


Figure 29. Simulation of the expansion of the magnetosphere for the low solar wind density period of May 10, 1999 (bottom panel) and the compression of the magnetosphere during the high solar wind density period of January 11, 1997 (top panel). Both images are on exactly the same scale and have exactly the same color bar.

Wind investigators have identified several extended intervals of anomalously low (<<1cm^{-3}) solar wind density within the last few years [*Richardson et al.,* 2000]. These events are most puzzling in that, unlike solar eruptive events that clearly herald major interplanetary and geospace consequences, there is no evident source of anomalous low-density solar wind on the Sun. *Usmanov et al.* [2000] tracked the low-density features of the May event back to about 20 solar radii with an inverse mapping technique. Their analysis suggests that the event was initiated by a low velocity excursion of the heliospheric current sheet toward the helioequator. A combination of this inverse mapping technique with SOHO/EIT images may make it possible to further trace these structures down to the solar surface and thereby discover their cause.

The anomalously low solar wind density allows electrons to stream out of the corona with essentially no Coulomb collisions forming a particularly strong and narrow beam of electrons streaming toward Earth [*Fairfield and Scudder,* 1985]. The SWE instrument on Wind is specifically designed to resolve features of this electron beam, or strahl [*Fitzenreiter et al.,* 1998], the temperature of which directly reflects that of the corona [*Ogilvie et al.,* 2000]. The extremely low solar wind density conditions of the May event allowed the energetic strahl electrons to reach 1 AU where they enter the Earth's tail lobes and precipitated on the polar cap. Polar/PIXIE observed uniform, very intense and unusual X-ray emissions caused by these electrons throughout the northern polar cap (Figure 30). Normal auroral oval emissions were absent in both X-ray and UV. The auroral cameras imaged the unlit southern polar cap, which had a normal X-ray and UV auroral oval and a quiet polar cap. This asymmetry indicated that the northern polar cap was connected to interplanetary magnetic field lines, thus providing interplanetary electrons preferential

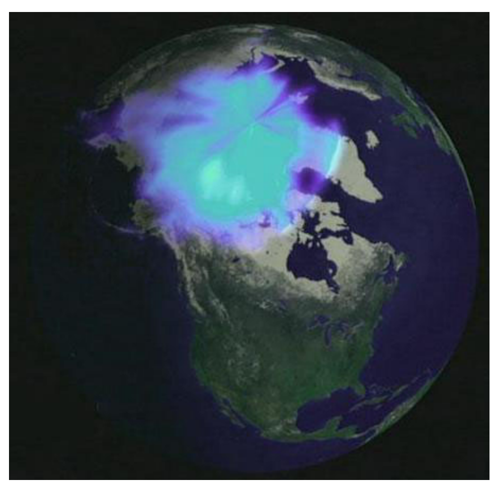


Figure 30. Bremsstrahlung X-ray emissions produced by the energetic electron strahl observed during the May 11-12 1999 "day the solar wind died" event. Because precipitation plays such a key role in upper atmosphere ionization and therefore controls ionosphere conductivity, X-ray images are extremely important to the understanding of particle acceleration mechanisms and global current systems.

access. The lower-energy component of the polar-cap electron spectrum probably came from the suprathermal (halo) portion of the solar wind electron distribution. The higher-energy components were associated with electrons accelerated in solar flares of coronal flare-like events [*Anderson, et al*., 2000].

The extreme expansion of the terrestrial dipole field on May 11 also resulted in a substantial decrease in energetic particle fluxes within the radiation belts beginning shortly after event onset and continuing for many weeks afterwards. Polar, in conjunction with SAMPEX, provided clear evidence that the radiation belts became more azimuthally symmetric as the solar wind pressure decreased. Polar/MFE found Pc 3-4 waves to be nearly absent in the dayside magnetosphere even though simultaneous observations in the upstream region indicated wave activity to be present in the foreshock. Since these observations occurred during the interval of average solar wind speed, this suggests that solar wind Mach number controls the growth of Pc 3-4 waves in the magnetosphere rather than instabilities associated with the flow of the solar wind plasma past the magnetosphere [*Le et al.,* 2000].

Perhaps the most surprising discovery related to this event has to do with ionospheric outflow. On many occasions, Polar investigators have presented evidence that solar wind plasma pressure is the primary driver behind heavy ion outflow [*Moore et al.,* 1999]. Given that, this very low solar wind pressure event might have been expected to produce little of the added energization necessary for ionospheric plasma to reach escape velocities and then reach the Polar satellite. In the spirit of nothing being simple, steady field aligned outflows were observed at a level comparable to solar minimum conditions [*Giles et al.,* 2001]. The observations establish a constant, minimum level of polar wind input to the outer magnetosphere (Figure 31).

Comparisons of the Great Storms

ISTP/GGS has built a catalogue of the magnetosphere's response to a large variety of solar input conditions. Several studies have taken this vast array of information and made progress toward sorting out patterns of dynamical behavior that can be generalized to future predictive efforts.

The Lyon-Fedder-Mobarry (LFM) MHD simulations also provided self-consistent fields for the relativistic electron dynamic modeling of *Hudson et al.,* [1999, 2000]. Figure 32 compares the simulated electron integral flux for four events, using an AE8MAX input spectrum and the equatorial plane fields from LFM to advance guiding center test particle trajectories. The most rapid inward radial transport and energization was seen for the May 1998 storm, and longest time scale for the January 1997 storm. Outer zone electron fluxes were transported radially inward by the MHD fields filling the slot region during all four storm comparisons. This type of hybrid modeling allows exploration of kinetic effects, such as the role of different seed populations within radiation belt dynamics.

In the next triennium it will be important to extend the ISTP catalogue of Sun-Earth events and to investigate the response of the magnetosphere to the new conditions associated with solar cycle decline. Recurrent high speed streams from the Sun should provide the opportunity to identify how the magnetosphere responses vary based on its immediate past history. We will also be

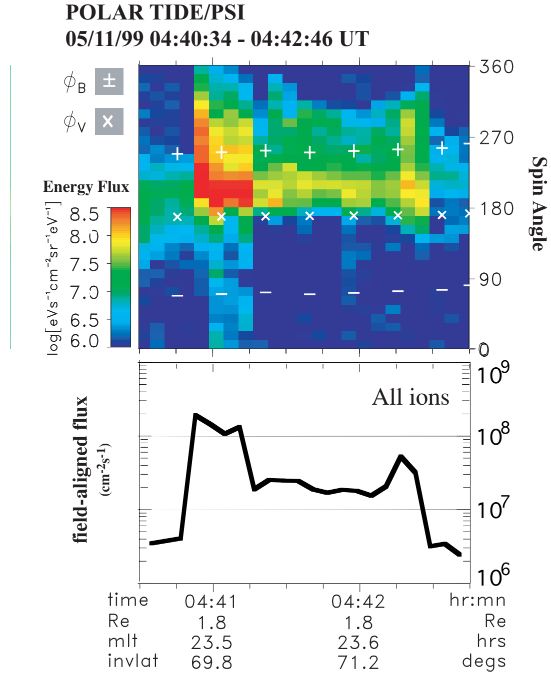


Figure 31. Nightside auroral zone ion upwelling observed during the May 11-12, 1999 "day the solar wind disappeared" event. Chosen as an example of the minimum auroral outflow to be expected, the figure shows that fluxes of 2. x 10^7 to 2 x 10^8 $cm^{-2}s^{-1}$ should not be considered unusual even for the quietest magnetosphere.

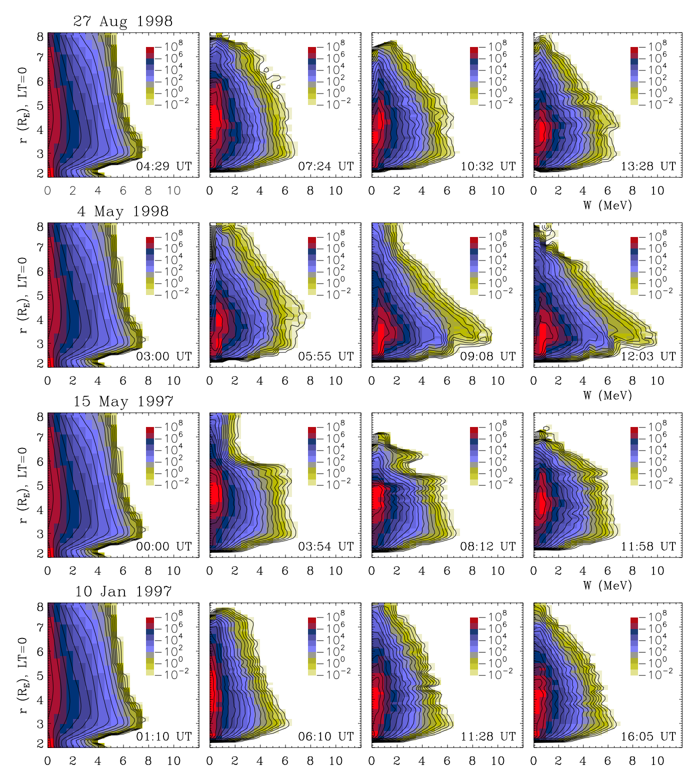


Figure 32. Simulated equatorial plane flux vs. energy and L for four geomagnetic storm events. A remarkable difference in radial transport rate for the different storms is evident.

able to understand how the enhanced inner magnetospheric energetic particle populations expected during this phase affect the dynamics.

The Role of Magnetic Reconnection

The ISTP Wind, Geotail and Polar spacecraft have all played leading roles in the recognition and understanding of magnetic reconnection processes throughout geospace with measurements from the magnetotail and flanks of the magnetopause with Geotail [*Hoshino et al.*, 1998; *Phan et al.,* 2001], in the deep tail with Wind [*Oieroset et al.,* 2000], in the solar wind with Wind [*Farrugia et al.,* 2001] and in the magnetosphere cusp layers with Polar [*Scudder et al.,* 2001]. Reconnection is the fundamental process that converts the plasma magnetic energy into kinetic energy and produces highly non-Maxwellian particle distributions with energetic tails and fast flowing particle streams. The high-resolution ISTP instruments are ideally suited for resolving the dynamics of these particle distributions and have been regularly used to remotely sense and diagnose reconnection events in several regions of geospace.

Nightside Reconnection

Geotail and Wind investigators have made significant contributions towards understanding reconnection processes and their consequences in the Earth's magnetotail region [see reviews by *Nishida* [2000]. Geotail observations have clearly demonstrated that earthward plasma flows with northward magnetic fields are predominant earthward of 20 R_E whereas tailward flows carrying southward magnetic fields are predominant tailward of 30 R_E [*Nagai et al. 1998*]. This places the typical site of near-Earth reconnection in the premidnight region near 25 R_E. Global MHD simulations of individual events clearly exhibit reconnection and show good agreement with ISTP measurements [e.g., *Wiltberger et al.,* 2000]. Also, a variety of distribution functions at various locations are found to correspond well to those produced by a 2-D, particle–in-cell numerical simulations [*Hoshino et al.,* 1998].

Oieroset et al. [2000], using Wind 3-D Plasma observations, were able to resolve earthward and tailward high-speed plasma flows consistent with the passage of a reconnection X line (Figure 33). The high-speed flows had a duration of several hours, unlike the shorter bursty bulk flows typically observed closer to Earth. The observations, which were analyzed in the context of the shear stress balance (Walen) test, imply quasi-steady reconnection in the mid-magnetotail (X_{GSE} = -60 R_E) during intervals of persistent northward IMF.

Dayside Reconnection

At the magnetopause, simultaneous measurements by Geotail and Equator-S, with Wind as an upstream solar wind monitor [*Phan et al.,* 2000] and later by Wind and Geotail with IMP-8 upstream [*Phan et al.,* 2001] provided the first two-spacecraft measurements of accelerated, bi-directional plasma jets consistent with reconnection near the sub-solar point and at the dawn flank magnetopause. The implication of these studies is that under steady IMF conditions reconnection occurs on a large scale, with a stable, extended reconnection line such that large-scale interactions between the solar wind and magnetosphere drive reconnection, rather than strictly local interactions.

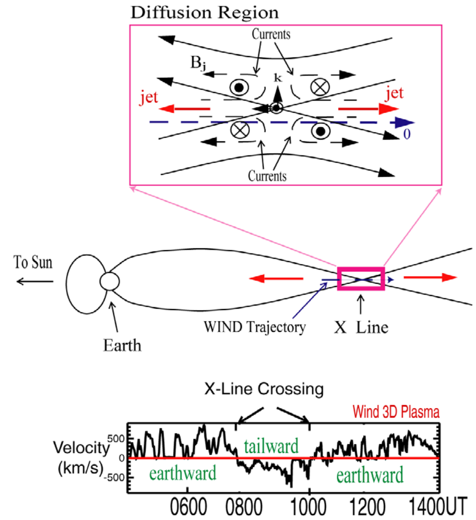


Figure 33. Top panel shows the diffusion region surrounding magnetic X-line within which reconnection occurs. Middle and bottom panels show the location of the diffusion region relative to Earth's magnetotail high speed flow data from Wind/3D taken during the event.

Polar observations provided the first observational evidence of northward-IMF anti-parallel reconnection [*Dempsey et al.,* 1998]. The existence of low-speed, D-shaped distributions mixed with cold plasmaspheric ions accelerated upon reflection from the magnetopause have been taken as evidence that low-shear, or component, merging can occur equatorward of the cusp as easily as northward-IMF anti-parallel reconnection poleward of the cusp [*Russell et al.,* 1998, *Fuselier et al.,* 1999; *Chandler et al.,* 1999]. The rate of reconnection was determined to continuously vary ± 20 percent [*Lockwood et al.,* 1998 and *Fuselier et al.,* 1999] and found to correlate with inward and outward motion (erosion and expansion) of the magnetopause [*Dempsey et al.,* 1999].

Another site experiencing significant reconnection, due to open field line creation by dayside merging, is along the high-latitude flank of the magnetopause. This magnetospheric "sash," first identified through MHD simulation [*White et al*., 1998], is a band of low magnetic field associated with the high latitude turbulent boundary layer [*Maynard et al.,* 2001].

Magnetosphere-Ionosphere Connections

Origins and causes of the Aurora

Understanding the aurora has always been important within the broader context of understanding magnetosphere dynamics. ISTP/GGS invested substantial resources toward multi-spectral imaging and has made major progress in understanding auroral processes as a result. The accomplishments have ranged from resolving micro-scale length acceleration processes, to quantifying the meso-scale processes of power deposition to the atmosphere, to establishing the global scale physics of the sources.

One of the first discoveries coming from ISTP was the long sought after direct experimental observation of DC, parallel electric fields [*Mozer et al.,* 1997]. The large amplitude parallel electric fields were confirmed to exist both at low and high altitudes [*Mozer and Kletzing,* 1998] and along magnetic field lines linking the plasma sheet boundary layer to the auroral zone [*Cattell et al.,* 1998; 1999].

After establishing that steady state and transient parallel electric fields existed, there remained the question as to how that power was transferred from the tail to the acceleration region. Polarized electric field variations associated with strong magnetic field fluctuations were found within the outer boundary of the plasmasheet at 4-6 R_E near local midnight [*Ober et al*., 2000; *Wygant et al*., 2000]. The associated Poynting flux was directed along the average magnetic field direction towards the ionosphere and was mapped to intense auroral structures (~20-30 ergs/cm^{2}s). The energy flux in the Alfvenic structures, when mapped to ionospheric altitudes, provided sufficient power (~100 ergs/cm^{2}s) to drive all auroral processes, including acceleration of upward flowing ion beams, electron precipitation, AKR, and Joule heating of the ionosphere [*Wygant et al*., 2000].

Closely following the discovery of parallel electric fields was the application of the electric field instrument and the plasma wave receivers toward the study of solitary wave structures. First identified by Geotail [*Matsumoto et al.,* 1994], they are systematically present in particle acceleration regions with sources of free energy [*Ergun et al.,* 1998] including the transition region of the terrestrial bow shock [*Bale et al.,* 1998].

VLF chorus was identified as another important driver of energetic particle precipitation, regularly observed within the inner and outer radiation belts [*LeDocq et al.,* 1998]. The absence of a reflected component within these closed field lines regions indicates the chorus is absorbed before reflection thereby determining the lifetime of radiation belt particles and the production of enhanced precipitation [*LeDocq et al.,* 1998; *Lauben et al.,* 1998].

The GGS multi-spectral imagers identified several previously unpublished auroral phenomena and identified production mechanisms for others that had been unexplained (see Figure 34). A hot-spot of auroral precipitation around 1500 UT was identified and traced to the plasma sheet. A series of papers using Polar UVI data underscore the effect of solar UV illumination on the aurora [*Liou et al.,* 1997, 2001; *Shue et al.,* 2001; *Meng et al.,* 2001]. A strong diurnal effect on auroral activity occurs, with more aurora seen when the nightside oval is in darkness than when the nightside oval is in sunlight. A controversial corollary then appears, that magnetospheric substorm dynamics can be controlled by the ionosphere through solar UV illumination as well as by solar wind/ IMF inputs. A "midnight void" in the nightside auroral precipitation region implies that a region of the magnetotail is inhibited from producing auroral precipitation while neighboring tail regions are quite active *Chua et al.* [1998]. *Anderson et al.* [2000] reported auroral X-ray observations by the PIXIE imager of impulsive events, termed convection-driven enhancements, in the morning sector during geomagnetic storms. The enhancements generally occurred shortly after a substantial increase in the cross-polar-cap potential drop, did not extend far into the pre-midnight sector, were not associated with substorm particle injections at geosynchronous orbit, but were associated with strong negative deflections in the horizontal component of the geomagnetic field in the morning sector. These convection enhancements can be contrasted with the typical substorm related auroral expansion shown in the adjoining frame. The pressure pulse aurora can propagate from the cusp around both flanks to the nightside in a period of only 10 minutes and has been well documented as the response of the magnetosphere to large solar wind discontinuities. The in-

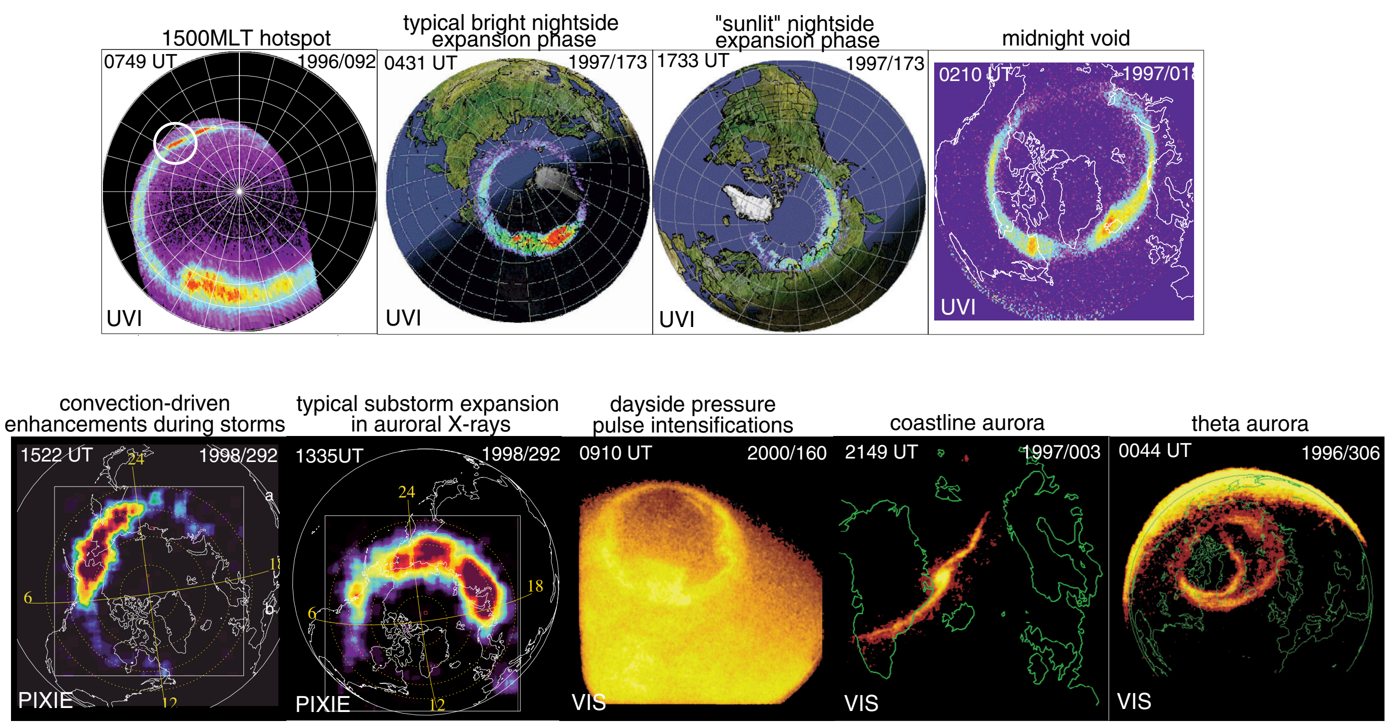


Figure 34. Polar UVI, PIXIE and VIS images showing examples of previously unpublished auroral phenomena and, in the case of the theta aurora, indicating phenomena for which ISTP identified production mechanisms which had been unexplained.

triguing possibility, first raised by Russian explorers in Siberia over a century ago, that geographic structures below aurora, such as a coastline, can have an influence on the development of auroral arcs has been supported by the high temporal resolution VIS images at 557.7 nm [*Frank et al.,* 1999]. The mystery surrounding production of the theta aurora was resolved [*Chang et al.*, 1998] as a response to antiparallel merging dynamics at the dayside magnetopause.

ISTP has advanced understanding of the temporal evolution of ionospheric convection patterns in several areas. *Maynard et al.* [1998a,b] used Polar measurements to resolve a long-standing controversy and establish how two-cell convection patterns evolve to four-cell patterns as the IMF clock angle decreases to near zero. The ground-based segment of ISTP, using SuperDARN and AMIE, discovered that the response to IMF changes is delayed by an average of eight minutes from the time an IMF change reaches the magnetopause, but occurs to some degree across the whole polar cap at once [*Ridley et al.*, 1997,1998, *Ruohoniemi and Greenwald*, 1998]. MHD simulations have largely verified this work [*Maynard et al.,* 2001a].

The Nature of the Substorm Onset Region

Considerable progress has been made in the past several years in identifying the position and nature of the onset of magnetic substorms, due largely by repositioning the Geotail spacecraft to radial distances of 10 to 20 R_E combined with the simultaneous global auroral images from Polar (Figure 35). The ISTP measurements focused interest on two major regions for the initial substorm instability: 1) the Near Earth Neutral Line (NENL) region at 20 to 30 R_E at the divide between earthward flows and tailward flows of plasma [*Nagai et al.,* 1998] and 2) the ring current at distances of about 5 to 10 R_E which has the highest plasma and magnetic energy densities and also their steepest spatial gradients [*Yahnin et al.,* 1997; *Frank and Sigwarth*, 2000; *Frank et al.,* 2000]. *Ohtani et al.* [1999] reached conclusions similar to *Nagai*, but noted that GOES 9 magnetic field observations were inconsistent with the NENL model.

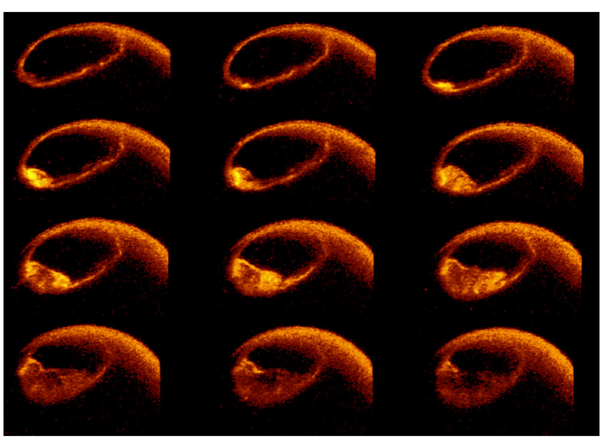


Figure 35. A series of Polar VIS auroral images shows the onset and expansion phases of an auroral substorm. The brightening of an equatorward auroral arc (frame 2 and 3) is the most reliable indicator of the onset of a magnetospheric substorm

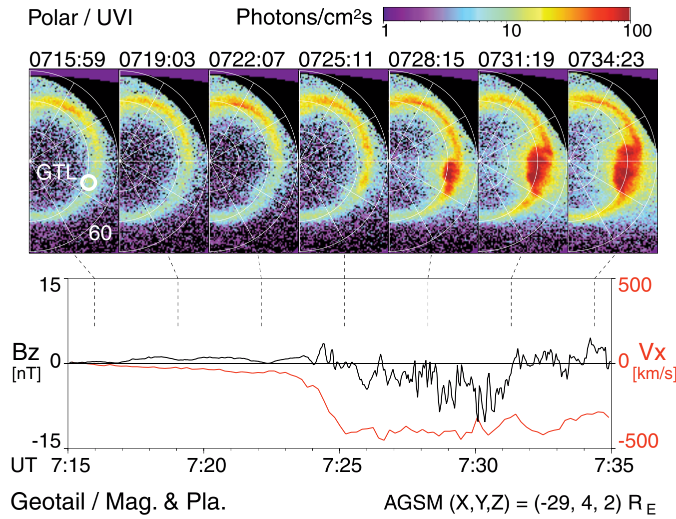


Figure 36. A series of Polar UVI auroral images is shown along with the magnetic field and plasma velocity measured by Geotail in the midnight magnetotail. An auroral substorm brightening near midnight can be seen to occur at the same time a plasmoid passes Geotail.

Liou et al. [1999, 2000] have shown that the brightening of an equatorward auroral arc is the most reliable indicator of the onset of a magnetospheric substorm. A recent study of the plasma flows in the plasma sheet as observed with the Geotail spacecraft has found a one-to-one correspondence with auroral brightenings [*Ieda et al.,* 2001]. This result, shown in Figure 36, supports the long-held idea that magnetic reconnection between 20 and 30 R_E is an important process that converts the stored magnetic energy in the magnetotail into the plasma kinetic energy which powers substorms. Other measurements suggest a more complex process at the onset of a substorm. For one thing, auroral brightenings coincident with Earthward flows and tailward plasmoids are often smaller "pseudo-substorms," i.e., brightenings at the poleward edge of the auroral zone [*Lyons et al.,* 1999]. The brightening of auroral arcs for the "classical substorms," which exhibit a fully developed expansive phase after onset, occur at the equatorward edge of the auroral oval. There are now questions as to whether there are two general types of substorms, the classical brightening originating at distances nearer to Earth and the brightenings that occur at higher latitudes connected to significantly greater distances. *Lui et al.* [1998] identified 102 auroral onsets when Geotail was in the magnetotail. The onset phenomena were spatially very localized with scales of the order of 1 R_E. It has thus been proposed that an earthward directed flow from a downstream near-Earth neutral line penetrates to radial distances of 5 to 10 R_E generating field-aligned currents that cause the auroral brightening [*Birn et al.,* 1996; *Shiokawa et al.,* 1997,1998; *Fairfield et al.,* 1999]. *Erickson et al.* [2000] found that the energy flow was outward from an onset region at the inner edge of the plasma sheet.

Magnetosphere particle energization and circulation

One of the primary objectives of ISTP was to discriminate between solar wind and terrestrial sources of plasmas and understand their interactions within the system. The discovery of a significant, persistent flux of polar wind escaping to the lobes of the magnetosphere showed that the ion outflows play a more significant role than predicted [*Moore et al.,* 1997, 1999; *Lennartsson et al.,* 1998, 1999; *Su et al.,* 1998]. ISTP observations make it clear that significant ion heating occurs as flux tubes flow through heating regions of the auroral zone [*Collin et al.,* 1998; *Krauklis et al.,* 1999]. At low energies, centrifugal acceleration acts as a primary energization mechanism [*Cladis et al.,* 1998]. In the inner tail current sheet, Geotail measurements found O^+ preferentially accelerated over H^+ by increasing Bz during substorms [*Nose et al.,* 2000]. In a similar open-closed magnetic field boundary region, *Ober et al.* [2001] observed direct perpendicular acceleration of O^+ by rapidly changing electric fields. These types of nonthermal effects have rarely been incorporated into models of terrestrial plasma outflow; however, now that ISTP has stressed the underlying importance of electric field structures with respect to wave-particle interactions, this area of physical modelling is being vigorously pursued.

The region dominated by the terrestrial outflows regularly extends well beyond the plasmasphere and, with sufficient solar wind influence, can dominate all but the far boundary layers and distant magnetotail [*Moore et al.,* 2000]. Direct observations of solar wind plasma entry into the magnetosphere dictate that at least the outer magnetosphere is solar wind dominated [*Moore and Delcourt*, 1995], and that a geopause separates the two regions. Indeed, the first global simulation work to include observed ionospheric outflows [*Winglee*, 1998] reached the conclusion that the geopause expands to fill the near-Earth magnetosphere and extends to great distances down tail when the ionospheric outflows reach peak magnitudes. Geotail observations support the idea that bursty bulk flows are the dominant means of energy transport in the tail [*Angelopoulos et al.,* 1999] although this is still disputed [*Paterson et al., 1998*].

Particles in the downstream tail mantle also enter directly from the solar wind [*Shodhan and Siscoe, 1996*] in addition to the cool ionospheric O^+ which flows down the tail along with protons from the magnetosheath [*Seki et al.,* 2000]. The O^+ is trapped on dayside closed field lines before being released onto open field lines created by dayside magnetic reconnection [*Seki et al.,* 2000]. Unusually dense magnetospheric plasma at lower magnetospheric latitudes in the tail have been seen near the flank magnetopause by Geotail [*Fujimoto et al.,* 1998,] and Wind [*Phan et al.,* 2000], particularly when the solar wind density is high [*Terasawa et al., 1997*], implying direct entry at this location. The entry is especially efficient during northward IMF which may be due to the Kelvin Helmholtz instability of this boundary that is enhanced under the condition of parallel interior and exterior magnetic fields [*Fairfield and Otto,* 2000; *Otto and Fairfield*, 2000].

The GGS spacecraft have made many advances beyond their original objectives. For example, the Polar/PIXIE X-ray Imager provided early confirmation [*Hawley et al*., 1998] of the new variable X-ray source XTE J1550-564 near Cir X-1 and the Polar/VIS cameras observed the progress of the Moon's shadow across the Earth's sunlit face during the solar eclipses of February 26, 1998 and August 11, 1999. The Polar auroral cameras were also able to confirm the existence of a neutral sodium tail on comet Hale-Bopp (Figure 37).

Several new opportunities can be pursued during the extended mission phase:

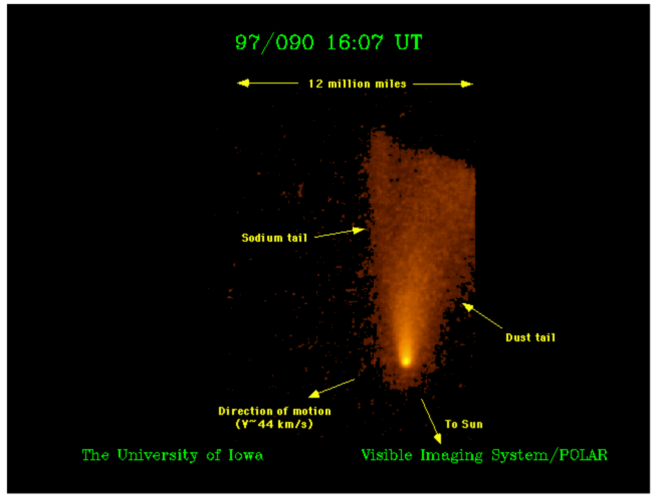


Figure 37. Image of comet Hale-Bopp taken by the POLAR/VIS camera clearly showing both the neutral sodium and dust tails.

Distant Magnetotail

Problem to be solved during the next 4 years:

What is the distance beyond which the magnetotail ceases to be fully connected to the Earth; and what factors or processes determine the mean and variations thereof?

Topics**:**

1) Location and structure of distant reconnection sites.
2) Structure of the distant tail: filamentary, dynamic or both?
3) Structure of the magnetopause at large distances; waves, instabilities, reconnection on the magnetopause.

Approach:

1) Use multi-spacecraft observations: Wind to measure the distant tail, upstream monitors (Geotail and ACE) to provide input conditions, and Polar and Geotail to measure near-Earth tail structure (cause and effects).
2) Develop 3-D models for possible structures and processes in the distant tail and magnetopause.
3) Use observations to identify correct physical models and use the models to visualize the 3-D structure of the distant tail and magnetospheric boundary.

Discussion:

Pioneer 7 and Pioneer 8 made intermittent observations of the magnetotail as they passed behind the Earth at 1000 and 500 R_E in the1960's. ISEE 3 and Geotail also frequently moved back and forth between the magnetosheath and magnetotail at distances up to 200 R_E in the early 80's and 90's. In none of these cases, however, were accurate simultaneous upstream measurements of the solar wind flow direction available, nor were detailed inner magnetosphere measurements available. Without such measurements researchers were unable to tell whether 1) a well collimated tail was simply moving to and fro like a wind sock in response to solar wind direction changes, or 2) the tail had broken up into many separate filaments. In 2004-2005, the Wind spacecraft will pass behind Earth about 320 R_E downstream when accurate upstream measurements are available from ACE and Geotail and inner-magnetosphere measurements are available to gauge magnetospheric response.

Post 2003, Wind will spend about 2-3 weeks in the deep magnetotail at least 320 R_E downstream during successive circuits of the Earth Return Orbit (Figure 38). These occasions will provide unique opportunities to investigate deep tail dynamics in conjunction with measurements by many other spacecraft in the inner magnetosphere. There are a number of important questions that can be addressed: Is there a semi-permanent distant tail reconnection site as postulated by several models? If so, is tail reconnection fundamentally different from near-Earth reconnection which is believed to be bursty and localized. What is the length of the magnetotail under northward IMF conditions? Recent global MHD simulation studies have found conflicting results. *Gombosi et al.* [1998] predict that the magnetosphere closes after about 1-2 hours of northward IMF with the tail reduced in length to about 50 R_E. *Raeder et al.* [1999], however, argue that the tail remains open and extended after many hours of IMF north. In general, Wind's location in the deep tail with so many near-Earth assets (Polar, Geotail, Cluster, IMAGE and FAST, etc.) will permit a truly global view of magnetospheric response.

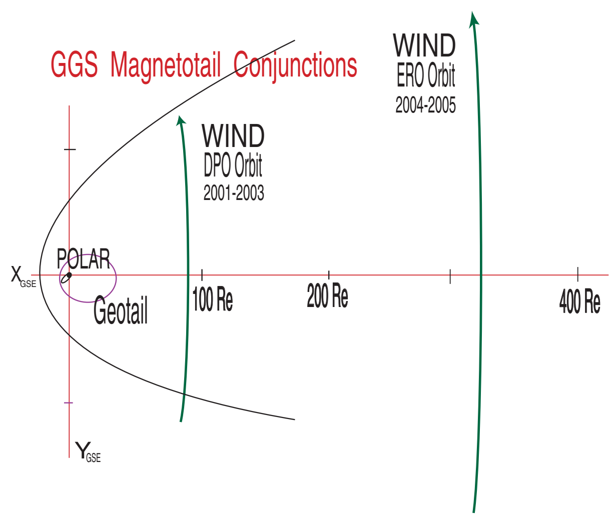


Figure 38. Typical orbits of Wind, Polar and Geotail during intervals of time when Wind is in the magnetotail in its Distant Prograde Orbit (about 90 R_E downstream) and later in its Earth Return Orbit (about 320 R_E downstream).

Gamma Ray Burst Observations

General problem:

Origin and localization of gamma-ray bursts

Recent work:

The KONUS Russian gamma-ray experiment on Wind was the first spacecraft to report detection of a giant gamma-ray flare on August 27, 1998. The gamma rays originated from SGR 1900-14, a high-magnetic field neutron star. This was the first galactic gamma-ray source to have a measurable effect on Earth's ionosphere.

Topics:

Where do Gamma Ray Bursts originate and why are there two distinct classes of bursts?

Approach:

The origin of gamma ray bursts is currently poorly understood. Recent evidence suggests that there are two distinct classes of GRBs based solely on their burst duration. Each probably has a different origin. Two Wind instruments KONUS and TGRS make fundamental GRB, soft gamma repeater (SGR), and hard x-ray transient measurements that could shed additional light on these and other questions concerning GRBs. Since the termination of COMPTON GRO and BATSE in June 2000, the Wind data have become even more critical to gamma ray burst studies. Wind is an important player in the Interplanetary Gamma Ray Burst Timing Network (IPN), which consists of Wind, Ulysses, and, until recently, the NEAR gamma ray detector. The combination of simultaneous GRB detections from these three spacecraft produce about one precise GRB localization per week accounting for about a third of all GRB counterpart searches and studies [*Cline et al.,* 2000]. The Wind-Ulysses-NEAR interplanetary-length baseline localized GRBs to within several minutes of arc, contributing important data to the fundamental question of the origin of GRBs. With Wind and Ulysses alone, the IPN can localize GRBs in a narrow plane. The Wind gamma ray detectors play a crucial role as the required third vertex in the long-baseline tripod of the GRB IPN.

Extended Neutral Atmospheres

General problem:

Jupiter is known to have an extensive neutral sodium atmosphere that has been observed with ground-based telescopes [*Flynn et al.,* 1994]. Atmospheric scattering prevents the study of this neutral sodium atmosphere while spacecraft are close to Jupiter itself; only the extended portions of the sodium atmosphere away from Jupiter can be studied from Earth-based ground observations.

Approach:

When the Polar spacecraft is oriented with its spin axis oriented normal to the ecliptic plane and the Earth's auroral oval is not in the field of view of the imagers, the VIS cameras will be retargeted for observations of Jupiter. The visible camera with its in-orbit location above the atmosphere, low-scatter off-axis optics, sodium filter and high sensitivity will be used to view the unexplored inner layers of Jupiter's sodium atmosphere as well as the extended atmosphere. An extended and frequent time line of observations can be established to determine of the level of variability of sodium in this atmosphere. Similarly, VIS can be used to determine if an extended neutral oxygen atmosphere exists around Jupiter and search for extended neutral atmospheres around the other near planets and the Moon. Similary, the sodium atmospheres of the Moon and the planet Mercury [*Mendillo et al.,* 1999; *Smith et al.,* 1999] can be observed.

Lunar Wake Studies

General problem:

How do unmagnetized solid bodies interact with the solar wind?

Recent work:

Wind measurements in the Lunar wake have greatly altered our picture of the region trailing Earth's Moon [*Ogilvie et al.,* 1996, *Farrell et al.,* 1996]. These measurements show that an ambipolar electric field set up by the subsonic solar wind electrons accelerates ions towards the center of the wake along the magnetic field, forming two ion streams with velocities greater and less than that of the solar wind. Plasma depletion extends far beyond the lunar light shadow, consistent with a rarefaction wave moving from the wake into the undisturbed solar wind. ULF waves and bi-directional electron flow are apparent on the entrance and exit sides of the wake. Instead of a trailing shock wave 2 or 3 R_L behind the fill-in region, the wake appears far more complex with an extension of at least 25 R_L.

Problem to be solved during the next 4 years:

It has become clear that a kinetic approach rather than fluid MHD is necessary to explain the ambipolar electric fields observed to drive the surprisingly stable ion beams and electrostatic wave activity seen in the flanks, though the basic theory of *Samir et al.* [1983] adequately explains the main points. The newly-developed model has direct application to the extensive wake expected to trail Space Station [*Farrell et al.,* 2001] and can be applied in general to the wakes of solid bodies in the collisionless plasma of the solar wind.

VI. Education and Public Outreach for ISTP SolarMax

ISTP Outreach Accomplishments

The EPO program of ISTP has been as diverse as the science mission itself. We have developed a wide variety of products and programs as we have tried to make an impact in formal education, informal education, and direct public outreach. ISTP has blossomed from a mission with little to no public exposure to the leader among Sun-Earth Connections missions.

We have developed several printed products to share the best of our imagery and information. The "Storms from the Sun" poster explores the science of coronal mass ejections and space weather for middle school to high school audiences. More than 140,000 copies of that poster have been distributed to date, and "Storms" was selected for inclusion in the Education Directory of exemplary materials published by the NASA Office of Space Science. We created a Spanish-language version of that poster –"Tormentas Solares" – that has been well used by teachers working with under-served Hispanic communities in American cities and in Spanish-speaking countries. Finally, in partnership with the Space Science Institute (Boulder, CO), we published "The Forecast" space weather brochure as an introduction to space physics for policy makers, journalists, and educators. That brochure also was selected for the OSS Education Directory.

On the World Wide Web, we invited the public into our scientific world with the Mission to Geospace web site (http://istp.gsfc.nasa.gov/outreach). The site was designed as a portal for journalists, teachers, and space aficionados to find easy-to-read information and engaging materials related to SEC science. Mission to Geospace is best known for its extensive library of articles and news releases and its collection of publicly accessible space weather imagery, media and data sets. In the past year, we also have added a special section on solar maximum and a collection of Spanish-language materials and web sites. In the year 2000, the site received more than 3.5 million "hits," and we are already on a pace for five million hits in 2001.

ISTP has been a key participant in the two major SEC-wide outreach activities in 2000-2001. The ISTP team was a primary partner with the Space Science Institute in Boulder in the development of the Space Weather Center traveling museum exhibit, providing extensive funding, content, imagery and technical support, including the writing of the exhibit text. This moderate-sized exhibit contained considerable imagery and three interactive displays. The exhibit to date has been at three museums, opening at the Denver Museum of Natural History and subsequently moving to the Maryland Science Center, and the Goddard Visitors' Center. It is scheduled at three additional sites, including the Adler Planetarium in Chicago. To augment the exhibit with education

programs, we then forged partnerships with the Maryland Science Center and the Visitors' Center to conduct two dozen public programs at the exhibit. ISTP staff also served as co-leaders of the Sun-Earth Days 2001 EPO event held on April 27-28, 2001. That event has provoked more than 50 education workshops and at least a hundred public science events.

Our proudest achievement in EPO– and most challenging work– has been the ISTP educator workshop program that has developed over the past 3 years. Since 1998, we have organized four education workshops, training more than 50 educators from 23 states in the science of Sun-Earth Connections. As a result of two of those workshops, educators returned to their home communities and states and conducted another 15 mini-workshops on SEC science for their colleagues and science supervisors. We estimate that we have reached at least 3000 to 4000 students through our workshop program (using a conservative multiplier of 60 students per teacher).

Our Approach and Philosophy of EPO

Today, our approach to EPO is different and is more educationally sound than when we began our program three years ago. Our emphasis is on presenting engaging and sound scientific content about Sun-Earth system science, rather than just mission programmatics. We focus on broad,fundamental themes and questions that fit into Earth science and physics curricula, and on concepts that meet existing science education/literacy standards. We start from what students are expected to know, rather than what we want them to learn, and we emphasize the everyday relevance and connections. We work with other SEC programs — particularly the Sun-Earth Connection Education Forum (SECEF) — to leverage and share resources and to create more comprehensive and inclusive products and programs. We involve educators directly in the development of our products and programs so that we might develop materials that are both scientifically sound and developmentally appropriate for students.

But, perhaps the most important lesson we have learned is that more students can be reached with a more lasting impact in EPO if we "teach the teachers." The teachers should learn as well as teach. An oft-overlooked part of the National Science Education Standards is the call to enhance and promote the professional development experiences for teachers. Specifically, the NSES states that: professional development for teachers of science requires learning essential science content through the perspectives and methods of inquiry; it requires integrating knowledge of science, learning, pedagogy, and students; it also requires applying that knowledge to science teaching; and it must be coherent and integrated. By taking this approach, we also leverage our efforts, as evidenced by our workshops described above.

The Future of ISTP Education/Outreach

Though we have achieved many things, we have much work to do. We have succeeded in promoting interest in ISTP science and in showing teachers and students that they can share in our science discoveries. But now we need to develop additional products and programs to allow teachers and students to put that scientific information to good use.

We have begun development of four major educational activities that should be fully developed, tested, reviewed, and printed in the next 3 years. "Seeing the Invisible" will be a middle to high school level lesson plan that explores how scientists use various parts of the electromagnetic spectrum to study the Sun and geospace. We are developing an extensive series of classroom experiments and investigations into the properties of magnetic fields, and why they are important to studies of plasmas and energy transfer in space and in the lab. Our "Follow the Sun" space weather tracking activities will provide students with the tools to make their own rudimentary analysis and predictions about past and future ISTP science events. Finally, we are developing a series of interdisciplinary lesson plans that allow students to explore SEC science through reading, writing, music, and art.

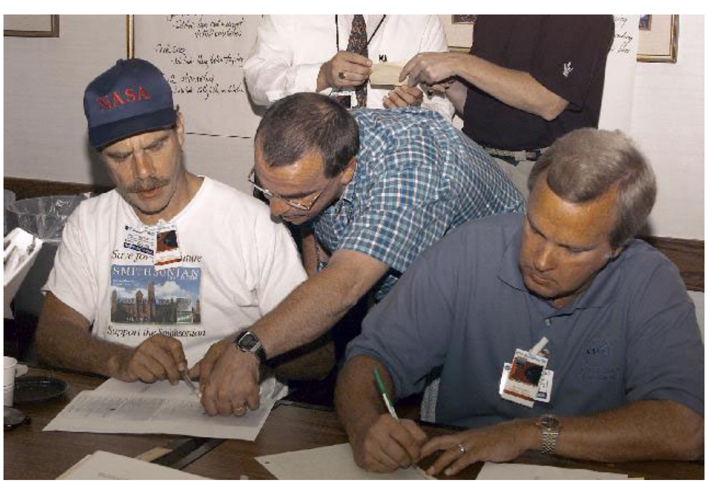
While there are many full-length documentaries available about Sun-Earth Connections, there are no resource videos that allow teachers and museum staffs to build and adapt their own multimedia presentations about our science. We plan to develop a narrated/closed-captioned video for science museums and planetaria, and another for classroom teachers. Such a resource video would include a broad sample of solar, auroral, and magnetospheric movies (organized thematically), spacecraft animations, computer models, plus music videos and video vignettes on key SEC topics.

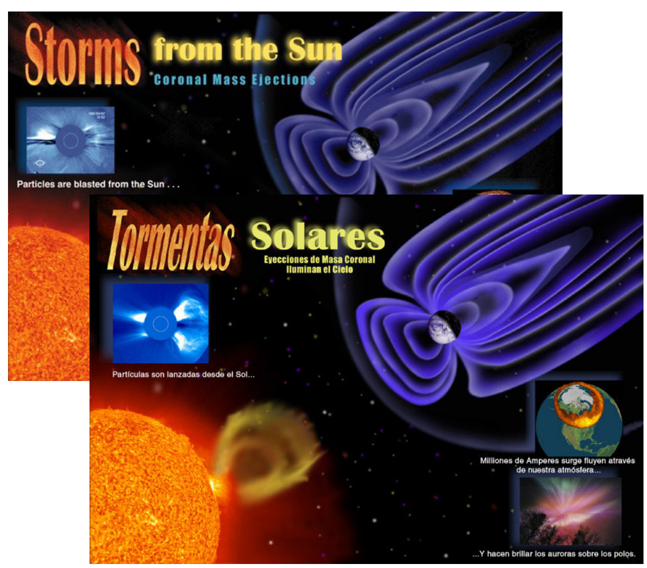
We will also develop posters on the aurora and on the magnetosphere/radiation belts, two topics that are not covered by existing NASA posters. Those posters will be packaged with "Storms from the Sun" and with SOHO's "New Views of the Sun" to make a complete SEC educational set. We also will produce low-cost, easily reproduced flyers for the non-scientist on selected SEC science topics (the first is "What causes the northern lights?").

One of the most significant contributions that we can make will be to continue and expand our series of ISTP education workshops. Working together with SECEF, we will host at least one education workshop at Goddard each year for as long as the ISTP mission continues. These future workshops will be targeted to groups that can extend the reach of the ISTP education program, including science textbook writers and editors, museum and planetarium professionals, professors of science education at the undergraduate level (in order to reach pre-service teachers), science reporters, and leaders of historically under-served minority and women's groups.

On the web, we will continue to expand the Mission to Geospace web site, developing new sections about historic space weather events and about "how we know"— how we develop and use different types of instrumentation to study our mostly invisible space environment.

Finally, we will compile these new materials, previous products, and our web site into a CD-ROM for distribution at national science education meetings and ISTP workshops. More importantly, we will work to distribute these materials to the ISTP science team and investigators across the country, conducting training sessions at science workshops to help scientists develop their own EPO skills and ideas.





VII. ISTP/GGS Status of the Assets

STATUS OF THE EXPERIMENTS

POLAR

INSTRUMENT	CAPABILITY	STATUS
MFE- Magnetic Fields Experiment	DC – 10Hz vector magnetic field	Normal
EFI- Electric Fields Investigation	3D Electric field Thermal electron density	Normal
PWI- Plasma Waves Investigation	Spectral and wave vector characteristics: 0.1 Hz to 800 kHz	Infrequent operation
CAMMICE- Change & Mass Magnetospheric Ion Composition Experiment	Energetic particle composition: 6 keV/Q to 60 MeV per ion	Normal
CEPPAD- Comprehensive Energetic Particle Pitch-Angle Distribution	Protons: 10 keV to 1 MeV; electrons: 25 to 400 keV	Normal
HYDRA	3D electron distributions: 3D ion distributions: 2 – 35 keV/e	Normal
TIMAS- Toroidal Imaging Mass-Angle Spectrograph	3D mass separated ions: l5eV/e to 32 keV/e	Normal
TIDE- Thermal Ion Dynamics Experiment	2D ions: 0 to 500 eV/e	Normal
UVI- Ultraviolet Imager	Far ultraviolet auroral imager: 130.4, 135.6, 140-160, 160-175, 175-190 nm	Normal
PIXIE- Polar Ionospheric X-Ray Imaging Experiment	X-ray auroral imager: 3 to 60 keV	Normal
VIS- Visible Imaging Experiment	3 low-light level auroral cameras: 130.4, 391.4, 557.7, 630.0, 656.3, 732.0 nm	Normal

POLAR

On March 27, 2001 the Polar spacecraft switched to its backup telemetry module and recovered the telemetry data from the TIMAS mid-energy particle experiment. TIMAS is now fully operational and is currently returning valid telemetry.

The remaining instruments on Polar are operating normally with the following exceptions. The Plasma Wave Instrument (PWI) operates only during periods of prolonged eclipse. The TOF stop pulses faded on the TIDE instrument so that mass separation by this instrument now requires post processing of the data. See section II-2A for an example of thermal ion mass analysis. PSI control of the spacecraft potential appears to be non-operational although further analysis of the ignition problem remains to be performed. Control of the spacecraft potential remains desirable but not as critical during current equatorial orbit configuration.

WIND

Of the eight instruments on WIND, three (SMS, EPACT, and WAVES) have experienced some minor performance degradation. Specifically, in May, 2000, the SWICS experiment, one-third of SMS, was turned off because of high voltage problems. Although there is considerable overlap with other portions of SMS, the lowest energy (10-30keV) ion composition measurements are no longer possible.

Of the four telescopes on EPACT, two (IT and APE) have reduced capabilities.

In August 2000, two-thirds of one 50 meter arm of the WAVES dipole antenna was lost, apparently due to metal fatigue. This has affected radiometer gain to some extent; however, detection of solar radio bursts and terrestrial emissions has not been visibly impacted. Similarly, the WAVES direction finding capability was also not measurably impacted.

A necessary switch to the backup spacecraft transmitter in August 2000 resulted in a 2dB gain in the WIND downlink telemetry.

WIND

INSTRUMENT	CAPABILITY	STATUS
MFI- Magnetic Field Investigation	DC – 10Hz vector magnetic field	Normal
SWE- Solar Wind Experiments	3D electron velocity distributions: 7 eV – 22 keV 3D ion velocity distributions: 200 eV – 8 keV	Normal
3DP- Three-Dimensional Plasma Analyzer	3D electron and ion distributions: eV – MeV	Normal
SMS	Energy, mass, charge composition solar wind ions: 0.5-230 keV/e	SWICS off
EPACT- Energetic Particle Acceleration, Composition, and Transport	Energy spectra electrons and ions: 0.1 – 500 MeV/nucleon Isotopic composition, Angular distributions	IT only measures elements. APE energy range limited
WAVES	Radio and plasma waves: dc – 14 MHz	Partial antenna loss
TGRS- Transient Gamma Ray Spectrometer	Gamma ray spectroscopy: 15 keV – 10 MeV	Normal
KONUS	Gamma Ray spectroscopy: 10 – 770 keV, high time resolution	Normal

GEOTAIL

INSTRUMENT	CAPABILITY	STATUS
MGF	DC – 8 Hz vector magnetic field	Normal except automatic range switching
EFD-Electric Fields Detector	Double Probe Electric Field	Normal except electron gun
PWI- Plasma Waves Investigation	Electric (0.5 Hz –400 kHz) and Magnetic (1 Hz –10 kHz) field waves	Normal
HEP- High-Energy Particles	Energetic and High Energy Cosmic Ray particles	Normal except highest energies
EPIC- Energetic Particle and Ion Composition	Energetic Particles and Composition 10 -230 keV	Normal
LEP- Low-Energy Particles	3D velocity distributions 7eV-42 keV ions, 6 eV-36 keV electrons	Normal except mass composition
CPI- Comprehensive Plasma Investigation	3D velocity distributions 1eV-50 keV ions and electrons	Normal

GEOTAIL

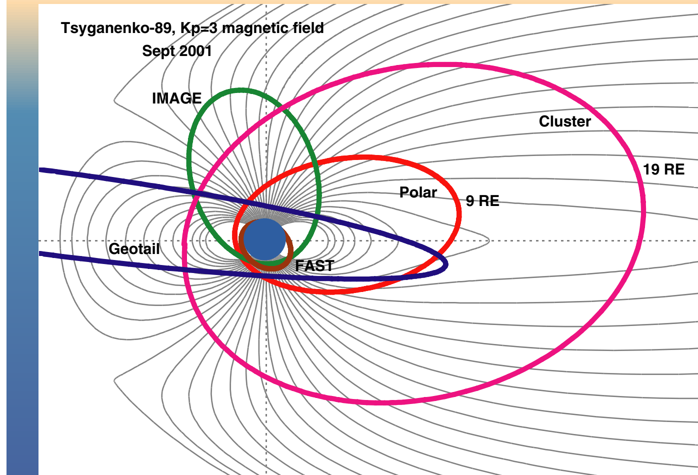
All seven experiments on Geotail are operating normally nearly 9 years after launch with the following exceptions. The mass spectrometer portion of the LEP experiment and a portion of the HEP experiment failed shortly after launch and the electron gun portion of the EFD experiment stopped working after several years. Automatic range switching on the Geotail magnetometer failed several years ago but the experiment operates normally in a fixed range which has little adverse impact on the science. Geotail has already survived the longest shadows it will encounter (more than twice the duration the spacecraft was designed for) so there are no foreseeable problems in continuing operation.

THEORY AND GROUNDBASED

INSTITUTION	CAPABILITY	COMPONENT
U of Maryland	Multiday movies of magnetosphere response to actual solar wind input	Theory & Modeling
UCLA	Origin of plasmas and simulation of polar atmosphere/ionosphere dynamics	Theory & Modeling
Dartmouth College	Evolution of the birth and death of the radiation belts	Theory & Modeling
U of Alaska	Magnetosphere-ionosphere-atmosphere coupling from auroral images	Theory & Modeling
U of Alberta	Canopus all-sky camera and magnetometer chain	Groundbased
British Antarctic Survey	SESAME multi-instrument measurements in the Antarctic of solar-terrestrial coupling	Groundbased
Stanford Research Institute	Sondrestrom radar observations of high latitude atmospheric dynamics	Groundbased
Johns Hopkins University/APL	SuperDARN observations of global ionosphere convection at both poles	Groundbased

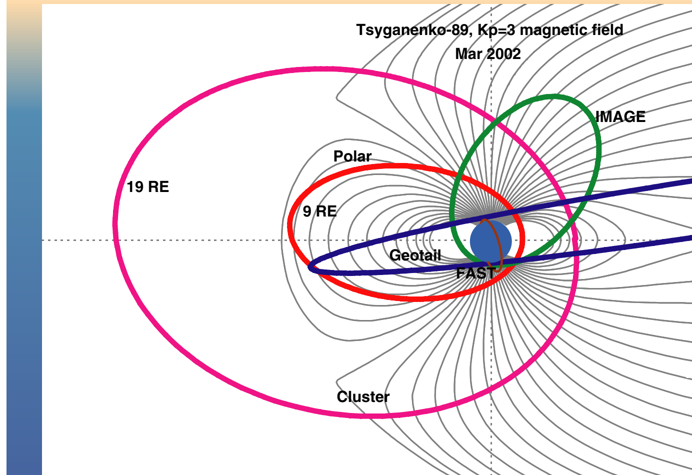
THE ORBITS PLACE THE SPACECRAFT IN THE HEART OF THE ACTIVE REGIONS

A. NIGHTSIDE EQUATORIAL OPPORTUNITIES



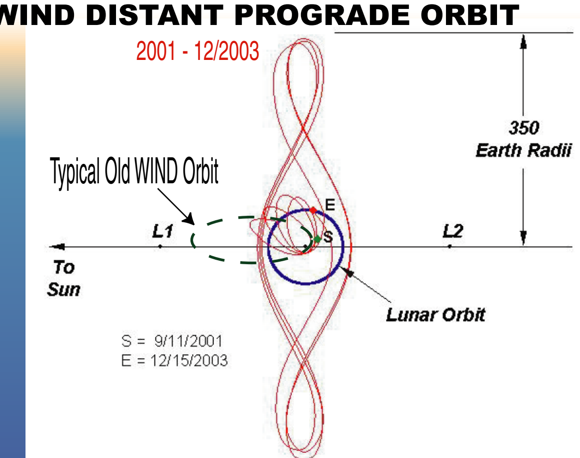
In the fall season each year, Polar and Geotail will sample the nightside equatorial region in nearly orthogonal planes with apogees near 9 R_E. Cluster will make north/south cuts through the plasma sheet near 17 R_E. This is ideal to examine the region between 6.6 and 20 R_E where any near- Earth instability is apt to have its origin.

B. DAYSIDE RECONNECTION OPPORTUNITIES



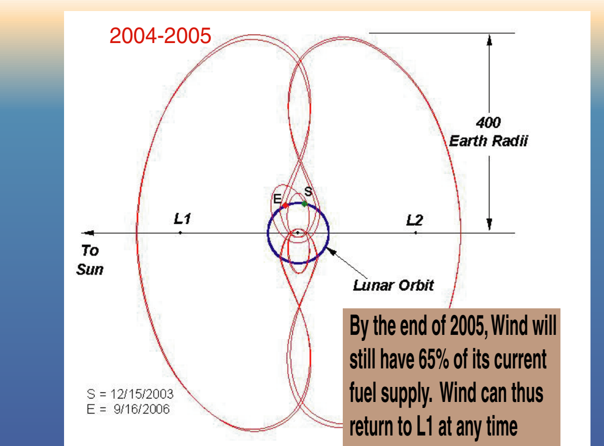
Modest magnetopause compressions will place Polar within the low latitude layers where reconnection is taking place or where its direct dynamical consequences can be detected. Simultaneous Geotail cross cuts through the equatorial plane and Cluster high-latitude reconnection measurements will document the extent and stability of dayside neutral lines.

C. WIND DISTANT PROGRADE ORBIT



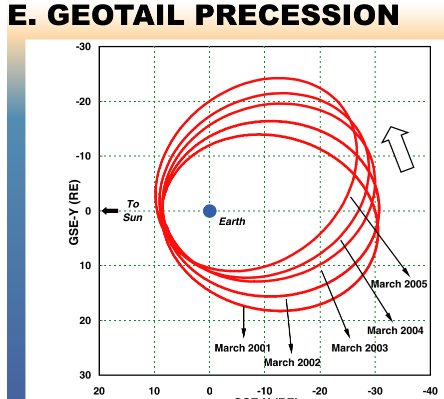
Wind spacecraft Distant Prograde Orbit (DPO) that with Ace and SOHO form a configuration useful for large scale solar wind structure investigation.

D. WIND EARTH RETURN ORBIT



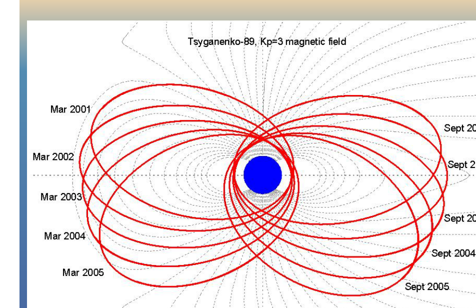
Wind Earth Return Orbit (ERO) with 400 R_E apogee will allow investigation of the deep magnetotail.

E. GEOTAIL PRECESSION



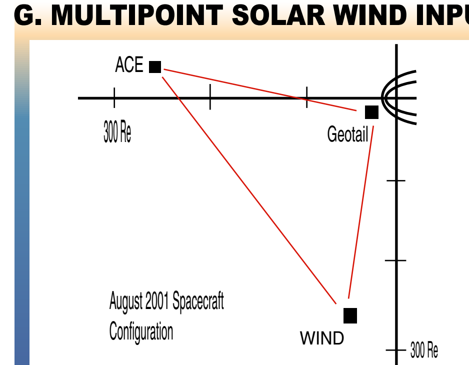
Geotail has completed its final maneuvers so that the apogee now drifts slightly as shown by the orbits for successive years in January.

F. POLAR PRECESSION



As the Polar apogee approaches and crosses the equator, successively deeper cuts at 5 to 9 R_E will be ideal for mapping the substorm ignition and dayside merging regions.

G. MULTIPOINT SOLAR WIND INPUT



Wind will form with Geotail and other near-Earth spacecraft a large baseline normal to the Earth-Sun line for the measurement of coherence lengths and geometries of large-scale interplanetary structures such as magnetic clouds.

A. Existing ISTP Resources

All of the considerable resources of the ISTP/GGS program have been in place and fully functional since early in 1996, just prior to the end of the previous solar cycle. The existing resources, SOHO, Geotail, Wind, Polar, Theory, collaborating missions, and Ground-based instruments, and complete ground data processing and distribution facilities constitute a 'Great Observatory,' capable of simultaneous observations and end-to-end analysis of the Sun, the interplanetary medium, magnetosphere, ionosphere, and upper atmosphere. The baseline approach to accomplishing the objectives outlined in this proposal is to utilize the resources already developed and set in place for the ISTP program. No further development costs are incurred. The existing, mature level of development of ISTP allows us to make use of a large previous investment, which establishes a highly leveraged position for ISTP/GGS. Spacecraft and program operations can be continued into the next triennium at modest cost.

B. Science Team Structure

The ISTP/GGS Science Team involves a distributed PI/Co-I team structure funded by the ISTP Science Office at GSFC. The Principal Investigator team infrastructure has been maintained, as recommended by the previous Senior Review, assuring minimal cost and overall operational stability. To address the evolving demographics of the research teams during the ISTP/SOLARMAX phase, the Science Office sponsored the funding of Extended Science Tasks to complement basic PI-Team funding. This very successful hybrid approach is explained more fully below in Section D. The maturity of the experimental investigations, the flight operations, associated software, and status of the ground data processing and distribution system were essential in ensuring the success of the Extended Science Tasks effort.

C. ISTP Ground System

The scientific achievements of ISTP have been matched on the ground by the continual improvements in data processing, access and validation, networks, and public data availability (the ground system was reengineered in the 1996-98 time frame and is covered in detail in Appendix B of the companion CDHF Senior Review proposal authored by W. Mish). These have been made possible by the prompt detection, identification, preliminary analysis, and distribution of results about solar-terrestrial events resulting in unprecedented scientific productivity and public awareness about the Sun-Earth connected system. The ISTP data are open to all scientists and their accessibility and scientific value are evidenced by the continued sponsorship of special sessions based on ISTP results presented at American Geophysical Union meetings each year, the number of special issues of scientific journals, and the worldwide presence of ISTP data in Solar Terrestrial research.

Central Data Handling Facility (CDHF)

The Central Data Handling Facility (CDHF) is the central repository and coordination point for the ISTP spacecraft, ground-based data (CANOPUS, SuperDARN, Sonderstormfjord, SESAME), and for data from other related missions, e.g., GOES and LANL geostationary spacecraft, SAMPEX, SOHO, FAST, IMP-8, ACE and Cluster. (The CDHF is fully described in the separate Senior Review proposal authored by W. Mish.) One of the CDHF's most important functions is the processing and delivery of Polar, Wind and Geotail level-zero data for the ISTP instrument teams within a few days of capture. The data capture and deliveries consistently exceed mission success criteria (>99 percent and 2-3 days). The CDHF further processes the level zero data into overview or summary data known as "key parameters" and ingests key parameters from the missions mentioned above. These key parameters are produced in near real time by the CDHF and are critical to the initial identification and evaluation of solar-terrestrial events. They constitute an efficient database which can be used as a catalog for the larger volume of data.

Science Planning and Operations Facility (SPOF)

Key to optimizing the science output of ISTP is coordination: coordination of operations to optimize opportunities for acquiring data needed to accomplish the scientific objectives; coordination in the identification of scientifically interesting periods (events) and event data products; coordination of the analysis of common data. In addition, the scientific operations environment of the SPOF allows a rapid reconfiguration of ISTP resources in response to Solar Terrestrial events. Various approaches, tools and procedures have been established to accomplish this coordination, which follows general guidelines developed by the Inter Agency Consultative Group (IACG) during the initial formulation of ISTP and related international solar terrestrial research programs. The SPOF is covered in detail in the CDHF proposal.

Flight Operations Team

Significant reductions in staffing of the Wind and Polar Flight Operations Teams have occurred in the last several years due to re-engineering of the ground system so that they currently are at a minimum level necessary for safe, routine spacecraft operations. When spacecraft emergencies occur, however, the FOT is strained to the limit of its capabilities with the result that occasional data loss occurs.

Deep Space Network (DSN)/Data Capture

Reengineering has resulted in a more reliable end-to-end protocol (TCP/IP) being used for the transmission of the playback data from the DSN stations, through JPL, to GSFC.

Flight Dynamics

Spacecraft maneuvering planning and support will remain a Flight Dynamics function; however, some cost savings have come from the elimination of selected products, *e.g.,* the definitive products, and reduction in frequency of production of others, *e.g.,* 70-day predicts produced monthly. Definitive accuracy requirements will be maintained in the predict products with unscheduled updates made, if necessary. Precise orbit design using a minimum expenditure of onboard fuel, as in the case of the unique orbits devised for Wind, will also continue to be a Flight Dynamics function.

Data Operations

The Data Distribution Facility (DDF) has been merged into the CDHF and fewer level-zero CD-ROMS are being produced and distributed with attendant savings in staffing, materials and mailing costs. The CDHF continues to make both the key parameter and special event data available to the scientific community in a timely and efficient manner.

Data Availability

Since the start of ISTP, the mission has supported a fully open data system. The ISTP project, through its end-to-end data system, provides the science community with an integrated environment, uniform data products, and science planning tools designed from the outset to enhance both the quantity and timeliness of the science return. Unique to ISTP is the integration of, and electronic distribution of a large number of key parameters from ISTP, ground assets, and associated missions. The data are openly available within a few days of capture allowing science analysis to be accomplished on the order of days rather than months. The entire space physics community makes use of the ISTP web based tools for planning, data display/analysis and data access and distribution.

Many of the ISTP principal investigators have developed web based analysis tools and further opened access to high-resolution processed data products [see, for example, <http://www-istp.gsfc.nasa.gov/istp/polar/data_products.html>. One of the challenges of the proposed extended mission will be to fine tune this direct access to the fully processed data sets, employing internet capabilities to provide more seamless access to the various analysis tools made available by the instrument teams.

Many of the ISTP principal investigators have also archived high resolution processed data products to the National Space Science Data Center. At a minimum, the archived data represent the "special observational events" coordinated by ISTP. Many instruments have archived their complete data set. These long term, calibrated, synoptic data sets are valuable both to compare global magnetospheric processes under a variety of solar input conditions and to provide ground truth testing materials for the various space weather models under development.

D. Operations, Strategy, Assumptions and General Approach

Sections A through C describe the overall technical and programmatic approach and the multiple elements available from the ISTP infrastructure which are already in place and will be carried into the next triennium. During the SOLARMAX phase, the Goddard Space Flight Center successfully implemented plans to:

(a) Reengineer Missions Operations resulting in a reduction in ISTP Ground System costs by more than 50 percent

(b) Reengineer Science Operations while maintaining critical elements to ensure the acquisition and production of *validated* data sets from all ISTP investigations, a fundamental science enabling function, and

(c) Promote "Competitive Science Programs" to fund research activities previously funded through Principal Investigator institutions and Guest Investigator programs.

A number of assumptions were made in this process which have relevance for the continued operation of ISTP, the most important being:

- Relaxation of some user requirements (*i.e.* possible increases in data loss or reduced coverage)
- Automated tools used to assist simplified planning and scheduling
- Co-location of spacecraft operations and flight operations teams (ACE, Wind, Polar, SOHO)
- Reduced distribution of CDs and increased use of Web-based tools (CDAWeb)
- Reduced faulty data recovery efforts

Taking into consideration the maturity of the ISTP spacecraft and operations effort, these impacts were considered to be acceptable risks.

In October of 1998 the GSFC Operating Satellites Project and other elements of the ground system were absorbed into the NASA-wide umbrella of the Space Operations Management Office (SOMO) and the Consolidated Services & Operations Contract (CSOC). This restructuring has had a dramatic impact on the costs associated with mission services and data services for the ISTP program. Prior to this reorganization, GSFC had provided several elements of the ISTP Ground System at no cost to the Office of Space Science (CDHF and associated elements, Flight Dynamics, Data Distribution Facility, *etc*.).

This proposal addresses three of the four categories of costs requested in the instructions, namely (1), (2), and (4), including both SOMO and science investigations costs. The costs associated with item (3) Science Center Functions are addressed in the separate (CDHF) proposal.

Science Operations, Data Visualization and Analysis

The goal of maximizing the science-per-dollar output from the ISTP/GGS program makes it necessary to minimize distributed and repetitive costs across the many PI institutions involved, particularly overhead and administrative, while maintaining full operation of the instruments and science data production and validation activities. For ISTP/SOLARMAX the ISTP Science Office encouraged all ISTP/GGS investigators to explore and propose new and innovative approaches to reduce costs, including the organization of scientific consortia, common instrument operations pools and engineering support groups. However, the recommendations from the previous Senior Review included the preservation of the PI team infrastructure while enabling expanded, but independent, Co-Investigator support. This hybrid model was successfully implemented by expanding the funding of ISTP Extended Science Tasks under a Competitive Science Program open to all ISTP selected investigators. More than 50 research proposals have been funded through this innovative approach.

A significant evolution has taken place with the enhanced open availability of data products and science tools to the scientific community by transitioning from dedicated hard copy products to unrestricted electronic access to the ISTP open data systems. Access to ISTP products via the NSSDC CDAWeb has grown explosively during the last 2 years. At the same time the parallel availability of CD-ROM sets has made possible the rapid implementation of ISTP key parameter mirror sites at several countries like Mexico, Brazil, Argentina, and Chile where electronic access is data rate limited or not cost effective.

Appendix A. Instruments and Principal Investigators

Investigation	Principal Investigator	Institution
Wind		
Radio and Plasma Waves	J. Bougeret/M. Kaiser	Paris Observatory/Goddard Space Flight Center
Solar Wind Experiment	K. Ogilvie	Goddard Space Flight Center
Magnetic Field Investigation	R. Lepping	Goddard Space Flight Center
Energetic Particle Acceleration, Composition, and Transport	T. von Rosenvinge	Goddard Space Flight Center
Solar Wind Ion Composition Study, the "Mass" Sensor, and Suprathermal Ion Composition Study	G. Gloeckler	University of Maryland
Three-Dimensional Plasma Analyzer	R. Lin	University of California at Berkeley
Transient Gamma Ray Spectrometer	B. Teegarden	Goddard Space Flight Center
Gamma Ray Spectrometer	E. Mazzets/T. Cline	Ioffe Institute, Russia/Goddard Space Flight Center
Polar		
Magnetic Fields Experiment	C. Russell	University of California at Los Angeles
Electric Fields Investigation	F. Mozer	University of California at Berkeley
Plasma Waves Investigation	D. Gurnett	University of Iowa
Hot Plasma Analyzer	J. Scudder	University of Iowa
Thermal Ion Dynamics Experiment	T. Moore	Goddard Space Flight Center
Toroidal Imaging Mass-Angle Spectrograph	B. Peterson	Lockheed Martin, Advanced Technology Center
Charge and Mass Magnetospheric Ion Composition Experiment	T. Fritz	Boston University
Comprehensive Energetic Particle Pitch-Angle Distribution	B. Blake	Aerospace Corporation
Ultraviolet Imager	G. Parks	University of California, Berkeley
Visible Imaging System	L. Frank	University of Iowa
Polar Ionospheric X-Ray Imaging Experiment	M. Schulz	Lockheed Martin, Advanced Technology Center
Geotail		
Electric Fields Detector	K. Tsuruda	Institute of Space and Astronautical Science
Magnetic Fields Measurement/Geotail Inboard Magnetometer	S. Kokubun/M. Acuña/D. Fairfield/K. Yamamoto	Institute of Space and Astronautical Science/Goddard Space Flight Center
High-Energy Particles	T. Doke	Waseda University
Low-Energy Particles	T. Mukai	Institute of Space and Astronautical Science
Plasma Waves Investigation/Multi-Channel Analyzer	H. Matsumoto/R. Anderson	Kyoto University/University of Iowa
Energetic Particle and Ion Composition	D. Williams	The Johns Hopkins University Applied Physics Laboratory
Comprehensive Plasma Investigation	L. Frank	University of Iowa
Ground-Based		
Canadian Auroral Network for the Origin of Plasmas in Earth's Neighborhood Program Unified Study	G. Rostoker/J.C. Samson	University of Alberta
Satellite Experiments Simultaneous with Antarctic Measurements	J. Dudeney/A. Roger	British Antarctic Survey
Sondrestrom Radar	J. Kelly	Stanford Research Institute
Dual Auroral Radar Network	R. Greenwald	The Johns Hopkins University Applied Physics Laboratory
Theory and Modeling		
Mission Oriented Theory	M. Ashour-Abdalla	University of California at Los Angeles
Theory, Modeling, and Simulation Support	D. Papadopolous	University of Maryland
Theory, Simulation, and Modeling	M. Hudson	Dartmouth College
Modeling of the Atmosphere-Magnetosphere-Ionosphere System	M. Rees	University of Alaska

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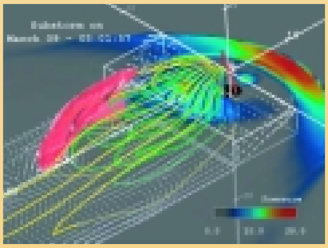

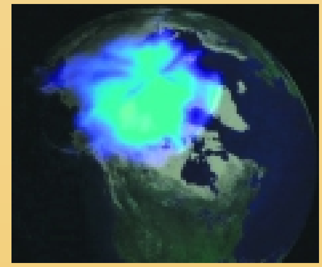

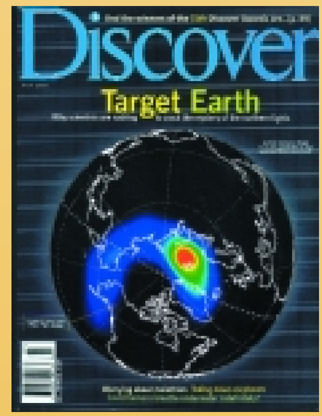

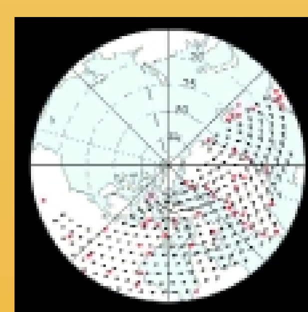

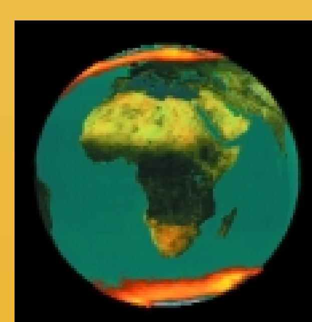

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