Imager for Magnetopause-to-Aurora Global Exploration (IMAGE)

Proposal to NASA Senior Review 2001 of Mission Operations and Data Analysis (MO&DA) Programs

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Executive Summary

IMAGE is the first space mission dedicated to imaging the Earth's magnetosphere and is the first mission to achieve global multispectral imaging of magnetospheric plasmas with time scales relevant to the development of substorms. The new imaging techniques include ultraviolet detection of helium ions and energetic hydrogen atoms; neutral atom imaging in three different energy ranges that encompass ionospheric outflow, solar-wind injection, plasma sheet, and ring current; and radio sounding, which remotely determines total plasma density. Early results from IMAGE have been reported in the 26 January 2001 issue of *Science* [*Burch et al.*, 2001a] and in eleven papers contained in the 15 March 2001 and 15 April 2001 issues of *Geophysical Research Letters*. Although IMAGE is not yet through its first year of science operations, it has already had a significant impact on the field. To date IMAGE has (1) convincingly shown the existence of the plasma tails predicted during magnetic storms by global magnetospheric convection models [*Burch et al.*, 2001a]; (2) discovered several new and unpredicted features of the plasmasphere including "shoulders," "fingers," corotating "voids," and isolated flux tubes [*Sandel et al.*, 2001]; (3) demonstrated that south-north transitions in the interplanetary magnetic field (IMF) produce the observed plasmasphere shoulders [*Goldstein et al.*, 2001]; (4) determined the energy-dependent injection and drift of energetic ions during magnetospheric substorms [*Burch et al.*, 2001a]; (5) made the first global images of the geomagnetic storm ring current, thereby identifying the development of a symmetric ring current during the recovery phase (**Figure 1**); (6) obtained the first global correlation between ring current precipitation and plasmaspheric density and used it to test the ion cyclotron theory of ring-current decay [*Brandt et al.*, 2001a]; (7) obtained the first global images of the proton aurora, established its cause and effect with correlative

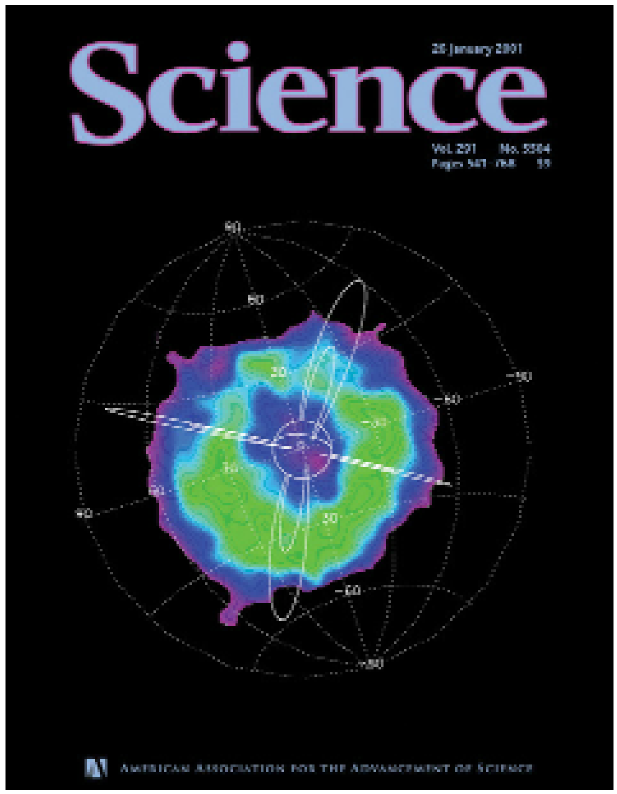

Figure 1. *The first published image of the symmetric ring current appeared on the cover of the January 26, 2001 issue of Science Magazine [Burch et al., 2001a].*

measurements of proton precipitation on FAST, and determined the dynamical relationship between electron and proton auroras during substorms [*Frey et al.*, 2001; *Mende et al.*, 2001a]; (8) discovered a neutral atom component of the solar wind, which allows it to be measured from within the magnetosphere [*Moore et al.*, 2001; *Collier et al.*, 2001]; (9) made the first measurements of interstellar neutral atoms from the inner solar system; and (10) obtained the first remote measurements of plasmaspheric densities using radio sounding [*Reinisch et*

After only one year of operation, IMAGE has provided an unprecedented look at the structure and dynamics of the inner magnetosphere and has made significant progress toward achieving its scientific objectives.

The IMAGE extended mission will study, during the declining phase of the solar cycle, the magnetosphere's dynamic response to recurrent storms from a new mid-to-low latitude imaging perspective.

al., 2001]. In addition to these significant early scientific results, IMAGE has appeared prominently in the popular scientific press [e.g., *Burch*, 2001a], receiving awards for technological achievement (from *Popular Science* and *Discover*) and for its education and public outreach (E/PO) program (e.g., several awards for the "Blackout" video).

The early results from IMAGE represent significant progress toward achieving the mission's scientific objectives. Each of the six IMAGE instruments has contributed significantly to the scientific accomplishments of the mission, in no small part because of the integrated nature of the payload and the resulting data stream, which uses a common format that facilitates the joint plotting of data. IMAGE has also contributed to the NOAA space forecasting activity through the ancillary real-time transmission of the entire IMAGE data set in addition to its baseline store-and-forward data mode.

While IMAGE is well on its way to achieving the full set of science objectives for the prime mission, an equally important extended mission will be possible because of the migration of the line of apsides of the IMAGE orbit toward lower latitudes (at a rate of 50 deg/yr) and the transition to the declining phase of the solar cycle (during which CME-driven storms are gradually replaced by recurrent storms associated with high-speed solar wind streams at corotating interaction regions). The lower-latitude apogee will be especially useful for (1) the measurement of the field-aligned distribution of energetic neutral atoms and hence the pitch-angle distributions of the parent ions; (2) the measurement of global ionospheric outflow over both the northern and southern polar caps; (3) higher spatial resolution imaging of the aurora over both hemispheres; (4) radio sounding of the dayside magnetopause; (5) the measurement of plasmasphere refilling rates using EUV imaging of helium ions; (6) radio sounding of the substorm-related changes in magnetic field line lengths when the IMAGE orbit is nearly field aligned; and (7) plasma wave propagation experiments to the Earth, including observations by our E&PO partner, INSPIRE, http://image.gsfc.nasa.gov/poetry/inspire.

During the extended mission, IMAGE will be the only spacecraft obtaining nearly continuous global auroral images, will provide stereo neutral atom imaging as soon as the first TWINS spacecraft becomes operational in 2003, and will continue to provide real-time space weather forecasting data to NOAA and other interested institutions. In its role as the first space weather satellite (analogous to the first geosynchronous weather satellite), IMAGE will be an important early complement to Living with a Star.

In the following section, the accomplishments of IMAGE are summarized according to the specific science questions addressed by this mission. In addition, other accomplishments that were either unanticipated or not directly related to the specific questions are summarized separately. Following these significant results, the new mission is introduced and discussed.

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SCIENCE SECTION

I. ACCOMPLISHMENTS TO DATE

The overall science objective of IMAGE is to determine the response of the Earth's magnetosphere to changing conditions in the solar wind. IMAGE addresses this objective by answering three specific science questions: 1) What are the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm time scales? 2) What is the directly driven response of the magnetosphere to solar wind changes? 3) How and where are plasmas energized, transported, and subsequently lost during storms and substorms?

Table 1 lists the six instruments that were designed to address these questions. It also illustrates their measurement capabilities. After one year of operation, each instrument continues to perform well and to contribute to the science objectives in a significant way.

The following sections are organized according to the science questions posed in our original proposal and highlight the contributions of the different instruments as well as of the theory and modeling program, which is an integral part of the mission.

A. What are the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm timescales?

1. Cusp Injection. Magnetosheath plasma is injected directly into the magnetosphere through the polar cusps. FUV SI12 (Spectrographic Imager, 121.8 nm channel) imaging of proton auroral emissions has made possible routine monitoring from space of the ionospheric footprint of the cusp and thus provides a means of investigating cusp plasma injection under varying solar wind conditions. **Figure 2** shows an initial sudden enhancement of the proton aurora triggered by the impact of an interplanetary shock on the magnetopause and the resulting magnetospheric compression [see *Fuselier et al.*, 2001]. The footprint of the cusp is observed as a "spot" located in the post-noon sector poleward of an incompletely developed main oval. (The longitudinally extended emission feature equatorward of the nominal oval maps to near geosynchronous orbit and may be produced by protons precipitating from the plasmasphere. See section C.6 below.) The cusp footprint is located where it would be expected to be observed for the case of high-latitude reconnection under conditions of

FUV SI12 images identify merging location in ionosphere for northward IMF.

Imager	Lead Investigator	Objectives	Measurements
LENA	Thomas E. Moore, NASA/GSFC	Image ionospheric outflow	Neutral atom composition and flux at 10 eV to 1 keV with field of view of 90°x360°, angular resolution of 8°, and energy resolution of 80%.
MENA	Craig J. Pollock, Southwest Research Institute	Image inner region of plasma sheet	Neutral atom composition and flux at 1 keV to 50 keV with field of view of 90°x120°, angular resolution of 8°, and energy resolution of 80%.
HENA	Donald G. Mitchell, Johns Hopkins Univ., Applied Physics Laboratory	Image ring current	Neutral atom composition and flux at 20 keV to 500 keV with field of view of 90°x107°, angular resolution of 8°, and energy resolution of 80%.
EUV	Bill R. Sandel, University of Arizona	Image plasmasphere	Extreme ultraviolet irradiance at 30.4 nm with field of view of 90°x90° and angular resolution of 0.6°.
FUV	Stephen B. Mende, University of California, Berkeley	Image electron and proton aurora; map geocorona	Far ultraviolet irradiance at 135.6 nm, 121.8 nm, and 140-190 nm with field of view of 15° and angular resolution of 0.1°; geocorona maps with three 1° field-of-view photometers.
RPI	Bodo W. Reinisch, University of Massachusetts, Lowell	Sound total plasma density gradients throughout inner magnetosphere	Transmit and receive radio waves with frequencies between 3 kHz and 3 MHz.

Table 1. *IMAGE Science Instruments*

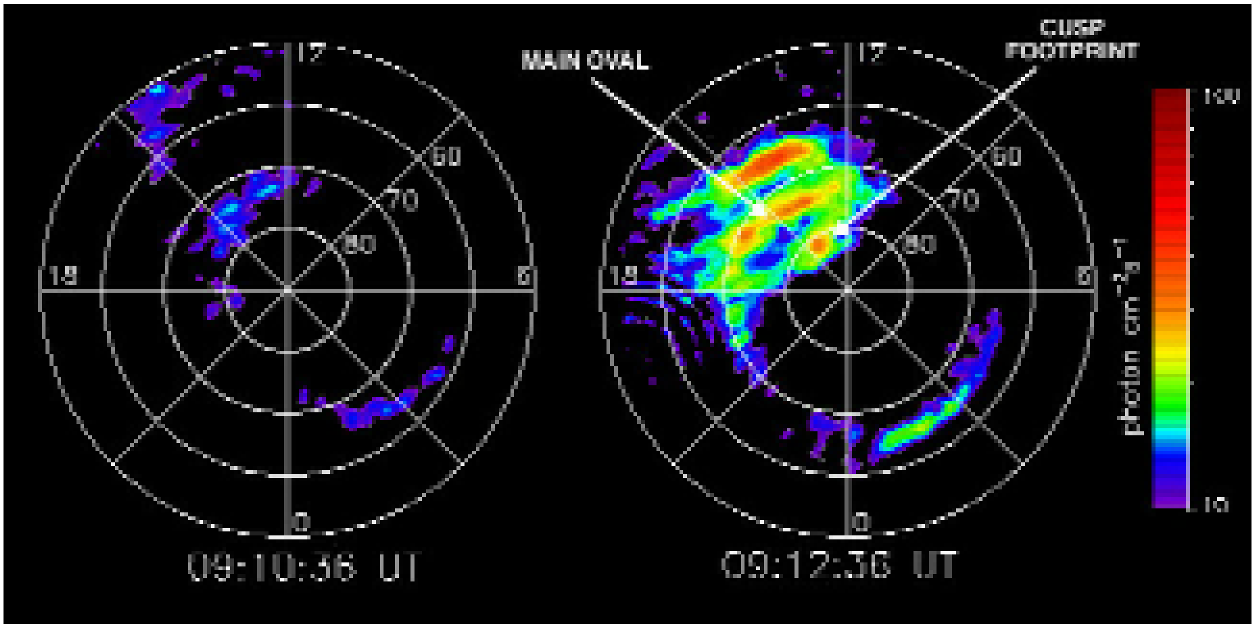

Figure 2. *Two consecutive snapshots of the proton aurora (Doppler-shifted Lyman-alpha emissions) immediately before (left) and after (right) the arrival of a CME-driven shock on 8 June 2000. The "cusp footprint" poleward of the "main oval" is the signature of merging at the high-latitude dusk magnetopause.*

northward B_z and positive B_y (to account for the post-noon offset). Examination of ACE data established that the IMF at this time was indeed strongly northward, with a significant positive B_y component. The Tsyganenko model was then used to confirm that the observed cusp emission occurred on field lines that mapped to the high-latitude duskside magnetopause, that is, to a region where, under the given solar wind conditions, the lobe field lines and magnetosheath field lines were oppositely oriented and thus antiparallel merging would be expected to occur. This event and several similar events that the IMAGE team has analyzed have confirmed predictions concerning the occurrence of high-latitude reconnection during northward IMF and corroborated observations showing the dependence of the location of the cusp footprint in local time on B_y [*Newell et al*., 1989; *Milan et al.*, 2000]. Further, the mapping of the cusp footpoint has provided information about the morphology of the high-latitude merging region, indicating that it is a narrow strip that extends tailward and comprises only a few percent of the total surface area of the magnetopause. The results of this analysis have important implications for our understanding of merging and plasma entry under varying IMF conditions.

2. Ionospheric Outflow. During magnetic storms, injections of heavy-ion (O^+) plasma from the high-latitude ionosphere are known to be an important source of magnetospheric plasma. In fact, the ring current is carried in large part by the motions of terrestrial O^+ ions during the largest storms. Much in-situ evidence has been obtained that the largest mass flux of ionospheric plasma comes from the dayside auroral regions, and that it feeds into the nightside plasma sheet through the polar cap lobes. However, this plasma travels slowly, and it was not clear that it could arrive at the nightside acceleration regions soon enough to be a factor in storm development.

Correlative analysis of IMAGE FUV observations of dayside auroral emissions and LENA observations of polar ion outflow has made it possible to investigate the timing between the impulsive input of energy into the ionosphere and the resulting ionospheric outflow. Images of the Earth's proton aurora from FUV SI12 indicate a temporally and spatially isolated brightening of the proton aurora in the post-noon sector in immediate response to a CME-driven shock that impinged on the Earth's magnetopause shortly after 09:10 UT on 8 June 2000 (**Figure 2**). A little over half an hour after the observed brightening, LENA detected a sharp increase in ionospheric plasma outflow (**Figure 3**)

LENA-FUV correlations show an immediate response of ionospheric outflow to the arrival of an interplanetary shock.

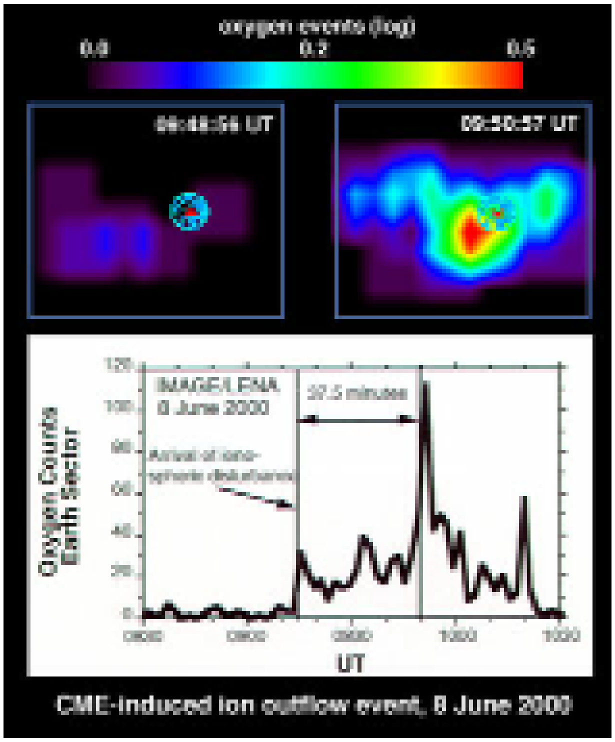

Figure 3. *A sharp enhancement of ionospheric O^+ outflow was triggered by the CME-driven shock on 8 June 2000. The top panel shows LENA images of ion outflow from the southern polar cap just before (left) and just after (right) the arrival of a cloud of O^+ ions at the spacecraft. The bottom panel shows the timing of the outflow enhancement relative to the ionospheric disturbance. IMAGE has established that outflow occurs almost immediately in response to impulsive input into the ionosphere [see Fuselier et al., 2001].*

[*Fuselier et al.*, 2001]. The time delay between the auroral response and the enhanced outflow is consistent with the travel time of ~30 eV neutral oxygen (created by charge exchange of outflowing O^+ with the exosphere) from the ionosphere to the spacecraft. This result indicates that the outflow was initiated immediately after the deposition of auroral energy as a result of the shock-induced magnetospheric disturbance. The promptness of the outflow and its association with the leading edge of the arriving CME indicate that the slowly-moving O^+ plasma enhancement had sufficient time to arrive in the nightside plasma sheet as the main phase of the storm was developing, and was thus a significant input to the ring current plasma. Its promptness also indicates that energy sufficient to initiate the outflow was deposited near or above the O^+ exobase (~350-1000 km) rather than at lower altitudes (e.g., around 250 km, where the bulk of the frictional ion heating occurs). This result localizes a geoeffective ionospheric outflow to the dayside subsolar region and constrains the initial acceleration region to be well above 250 km altitude.

3. Global Polar Cap Density Structure and Dynamics. From the analysis of RPI echoes we are able to observe significant global density variations in the polar cap on the time scale of the IMAGE orbit [*Henize et al.*, 2001]. **Figure 4a** shows the density distribution from one pass of IMAGE across the polar cap during quiet times (low Dst and no polar cusp crossing) when the spacecraft was at an altitude above 4 R_E. These densities have been determined from mapping RPI echoes into the polar cap region using the virtual range measurements. Routine true height inversion analysis of the RPI echoes is in the process of being completed and will provide density profiles to within an error of less than 10%. The density structure of the polar cap is represented by the color bands in this figure. During quiet times polar cap densities are essentially spherical and do not vary noticeably with longitude and only slightly with latitude (excluding the polar cusp).

From the analysis of RPI echoes we are able to observe significant global density variations in the polar cap on the time scale of the IMAGE orbit.

Figure 4b shows the polar cap density structure during the main phase of the 6 November 2000 storm. The key result of these observations is that during disturbed times the polar cap density structure is extended upward on the dayside as a highly variable region of enhanced densities. Variability of polar cap densities during disturbed times may imply significant Joule heating of the plasma in the polar cap region, subsequently giving rise to enhanced flow of ionospheric plasma into the magnetosphere. A systematic study of changes in the polar cap density is currently underway. The results presented in **Figure 4** come from only two orbits of IMAGE. Previous studies of global polar cap density structures [e.g., *Persoon et al.*, 1983] depend on the statistical analysis of many years worth of observations.

B. What is the directly driven response of the magnetosphere to solar wind changes?

Research over the past decade has led to a distinction between changes in magnetospheric plas-

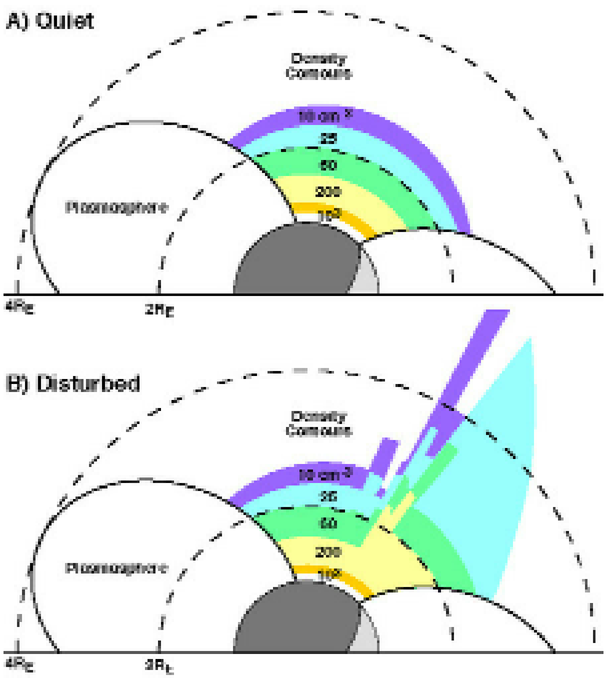

Figure 4. *RPI sounding produces 2-D images of the altitude distribution of polar cap ion densities in the IMAGE orbit plane [Henize et al., 2001].*

mas and fields that result directly from changes in the solar wind and IMF and the more impulsive and dynamic changes associated with the substorm expansion phase. Some of the directly-driven responses (e.g., inward motion of the magnetopause, equatorward motion of the polar cusp, and thinning of the plasma sheet) are attributed to the growth phase of magnetospheric substorms, while the more intense events, associated with long periods of strongly southward IMF and high solar wind velocities and densities, are thought to be responsible for the build-up of the geomagnetic storm ring current. These directly-driven responses are global effects that are best studied with global imaging, as is done with IMAGE. They manifest themselves in several ways, which may be classified as plasmasphere and ring current responses.

1. Plasmasphere Response. A long-standing controversy has existed about the theoretical predictions of long plasma tails in the dusk hemisphere during magnetic storms. Spacecraft in geosynchronous orbit, as well as elliptically-orbiting spacecraft such as OGO-5, have for many years observed outlying enhancements of plasma density that could be interpreted as islands of plasma or as plasma tails. There was no way to resolve this controversy without global imaging, and one of the first scientific results of IMAGE was to resolve it in favor of the plasma tails [*Burch et al.*, 2001a; *Sandel et al.*, 2001]. However, in addition to the plasma tails, IMAGE has also observed other longitudinal gradients in the plasmapause such as "shoulders," "fingers," "voids," and isolated flux tubes. The left-hand panel of **Figure 5** shows an example of a plasmasphere with a tail and a shoulder. While the theory of *Grebowsky* [1970] adequately accounts for the development of plasma tails during the enhanced convection of magnetic storms, the

EUV images have demonstrated that IMF changes can have immediate effects deep in the magnetosphere by forming the newly observed plasmaspheric shoulders.

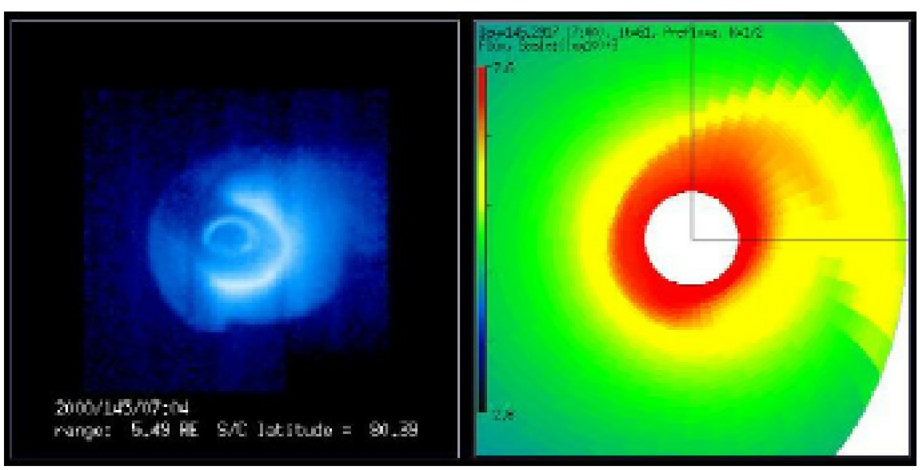

Figure 5. *(left panel) EUV image showing a morningside plasmaspheric shoulder (bottom, middle) and duskside tail (upper, right). (right panel) A Rice Magnetospheric Specification Model simulation of these features for the same magnetospheric and solar wind conditions [Goldstein et al., 2001].*

other features had not been predicted and require explanation. Using the Rice University Magnetospheric Specification Model, *Goldstein et al*. [2001] have demonstrated that the development of the shoulder is a result of residual shielding of the convection electric field, which causes a reverse eddy of convection in the dawn sector when the IMF rotates from northward to southward [**Figure 5, right panel**].

2. Ring Current Response. IMF changes directly drive other magnetospheric responses as well. The HENA instrument has observed the development of an asymmetric ring current (open drift paths) and its evolution into a symmetric ring current (closed drift paths) during several magnetic storms [*Brandt et al*., 2001b]. In this research, it has become apparent that transitions between northward and southward IMF are associated with rapid changes from the closed drift paths back to open drift paths. An example of this behavior is shown in **Figure 6**, which shows ENA images obtained by HENA in the energy range 16-50 keV. A rapid change in IMF B_z from northward to southward was followed by the rapid loss of the ring current all across the day side (compare panels b and c of **Figure 6**). These observations were reproduced using the ring current model of *Ebihara and Ejiri* [1999]. This result would have passed unnoticed without global ENA observations from IMAGE.

HENA images have shown that IMF north-south transitions cause a rapid shift of the ring current from closed drift paths to open drift paths.

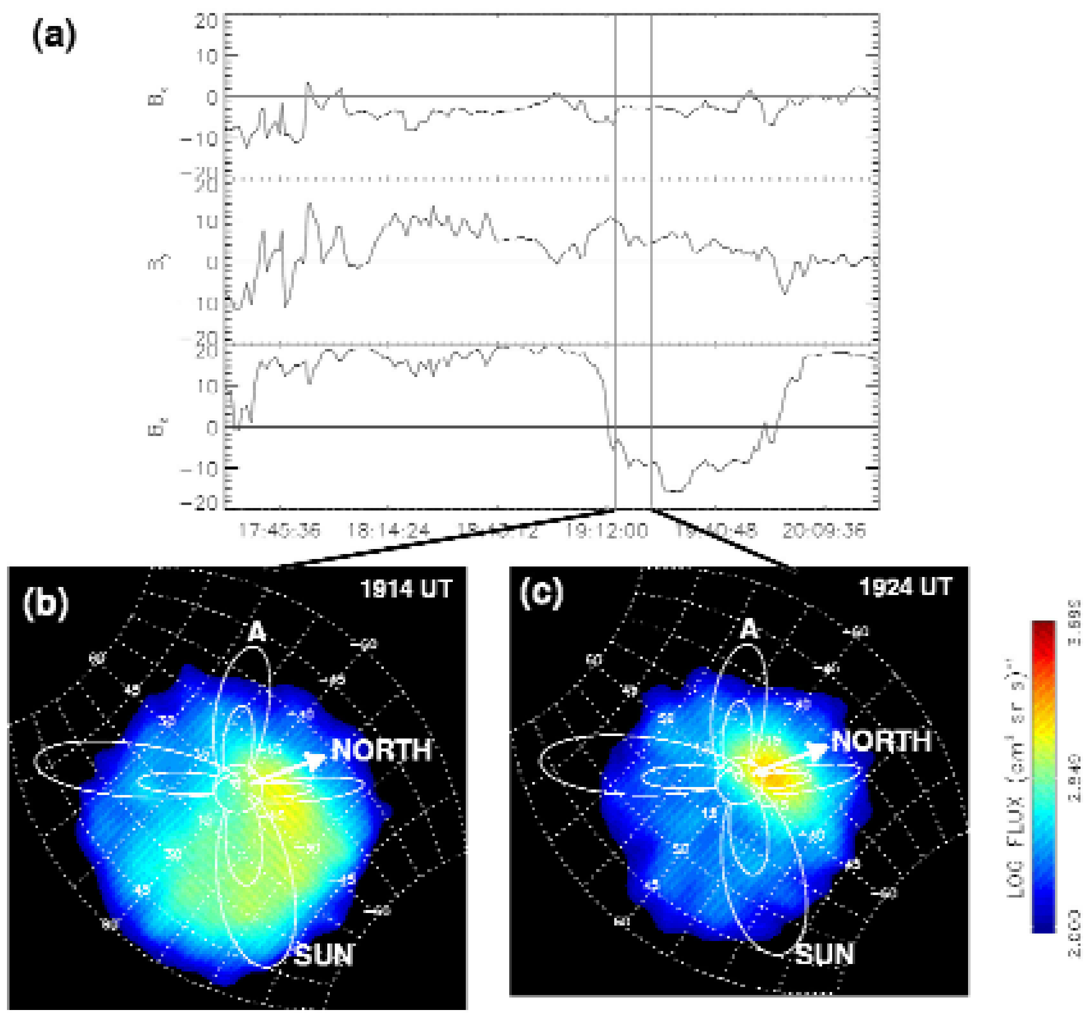

Figure 6. *ENA images show a transition from closed to open drift paths as the IMF changes from northward to south - ward. (a) the IMF measured by WIND; (b) and (c) HENA images [Brandt et al., 2001b].*

C. How and where are magnetospheric plasmas energized, transported, and subsequently lost during storms and substorms?

1. Storms, Substorms, Plasma Sheet, and Ring Current Injection. The IMAGE mission has determined fundamental differences between storms and substorms with regard to the injection of energetic particles into the inner magnetosphere. In the case of substorms, the plasma-sheet ion injection at energies above 10 keV rarely penetrates deeper than 6 or 7 R_E in the nightside equatorial magnetosphere. The energetic ions then drift by the well-known curvature and gradient drift mechanisms, before leaving the magnetosphere through the magnetopause along the dusk flank and the dayside. The lower-energy ions (less than around 10 keV) do not undergo drift dominated by magnetic gradient and curvature. Rather, they appear to stagnate on the night side. At even lower energies, the transport of injected ions may be dominated by convection, with ions drifting toward the day side via either dusk or dawn. **Figure 7** illustrates this ENA evolution observed by MENA and HENA during the later stages of a substorm (rows A, B, C, at 1100 UT) and well into the recovery (rows D, E, F, at 1140 UT). In the top row, strong injection is seen at 8.6 keV on the nightside while higher energies have drifted well past the dusk meridian. Forty minutes later, the lower energy end of the ring current injection has diminished in intensity while the higher energies have drifted to the dawn meridian.

For large magnetic storms, the ions in the 10 to 100 keV energy range penetrate much closer to Earth during the main phase injection, where (as noted in section B.2) they drift on closed drift paths, forming a symmetric ring current [*Burch et al.*, 2001a]. Storm-time behavior differs from the sub-

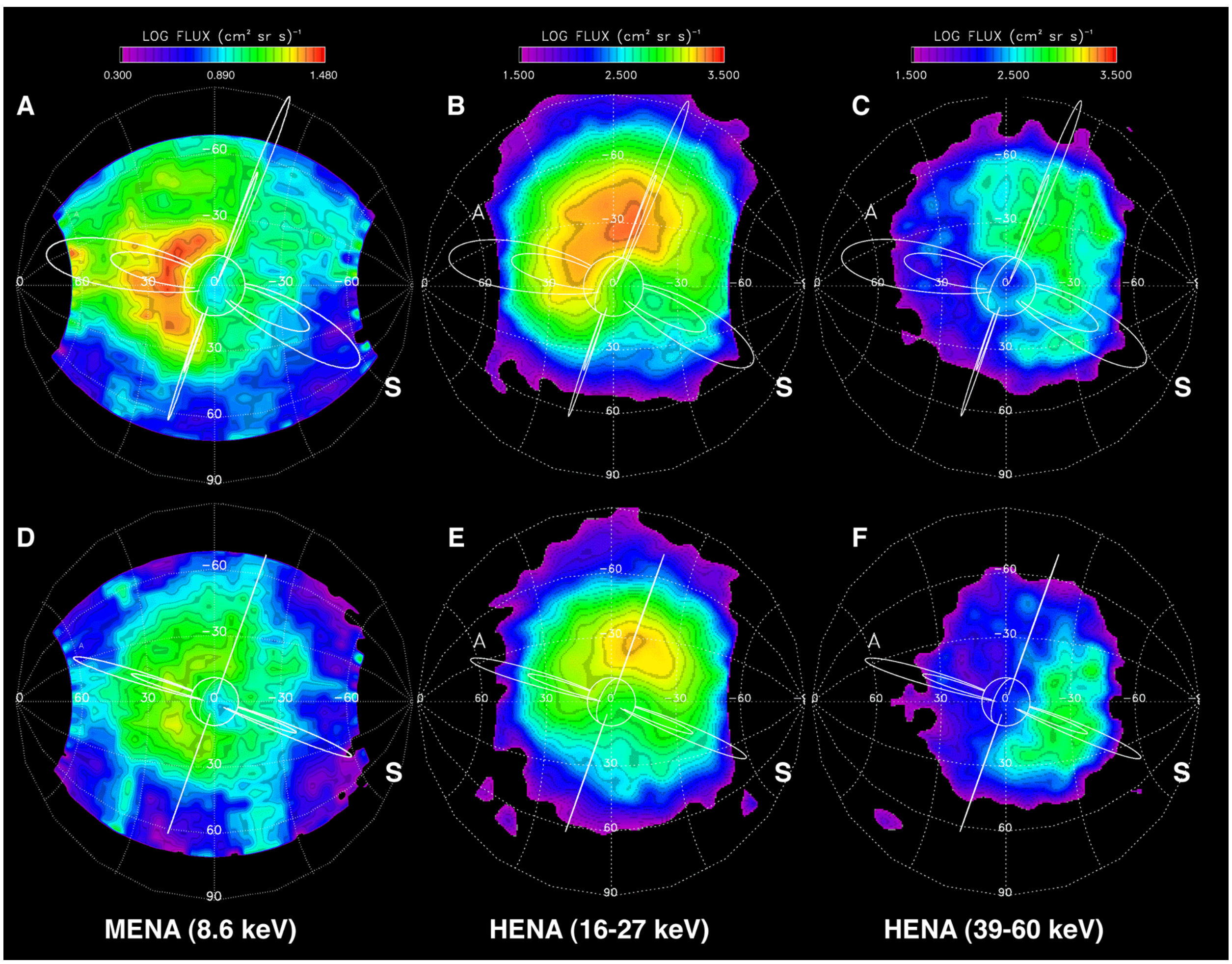

Figure 7. *MENA and HENA images from 10 June 2000 (top row, 1100 UT; bottom row, 1140 UT) show the evolution of ring current injections in the later stages of a substorm. Images such as these and others from magnetic storm periods have determined fundamental differences between storm and substorm injections [Burch et al., 2001a].*

storm case, where the energetic ions remain concentrated on the night and dusk sides, until they are lost from the magnetosphere after one to a few hours. In large storms, once the ions become trapped, they drift for days on their closed, nearly circular drift paths, gradually diminishing in numbers as they are lost by charge-exchange, coulomb collisions, and wave-particle interactions.

2. Deconvolved Substorm Ion Distributions. Much can be learned about the Earth's energetic ion environment from the neutral atom images obtained with the HENA, MENA, and LENA instruments on IMAGE. However, extracting ion distributions from these images is required to investigate the complete dynamics of the inner magnetosphere during disturbed times. Ion distributions have been deconvolved from HENA and MENA images obtained during storms and substorms using the technique of *Perez et al.* [2000, 2001]. **Figure 8** [*Burch et al.*, 2001a] shows an example of the deconvolved ion distributions obtained with this technique from the HENA substorm observations presented in **Figure 7** (middle and right-hand columns). The ion distributions shown are solutions to a non-unique inverse problem and represent the best fit in the Bayesian sense when there is no prior knowledge of the ion distribution. As noted by *Perez et al.* [2001], owing to the fall-off of exospheric density with altitude, the deconvolved ion images at times show peaks at larger radial distances (6-7 R_E) that are not correlated with strong peaks in the ENA images. Understanding such features is the subject of ongoing investigation.

3. Plasmasphere Refilling and Ducts. The outer plasmasphere has been sampled by previous spacecraft but never before probed remotely from space. RPI radio soundings show large regions within and beyond the plasmasphere to be permeated by field-aligned irregularities or ducts, which strongly influence high-frequency wave propagation. These ducts make possible the study of an important class of magnetosphere-ionosphere plasma interchange processes. It has been found that the RPI waves can propagate efficiently to great distances along field lines within these plasma ducts extending down into the northern polar region and into the conjugate hemisphere near and within the plasmasphere. The ducts are slight density depletions, estimated to be down about 10% from their surrounding field lines.

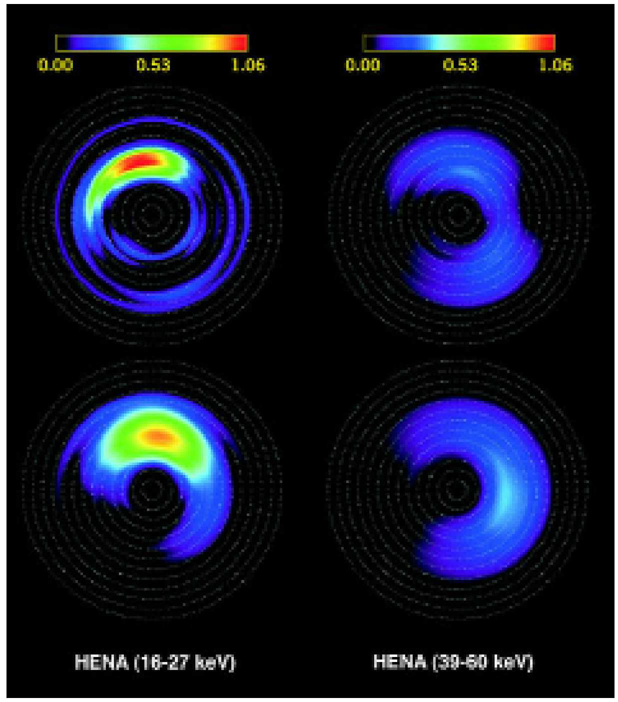

Figure 8. *Ion distributions deconvolved from HENA neutral atom images show the evolution of ions in two energy ranges during the last part of extended substorm activity and the recovery phase of the 10 June substorm. Plotted is the total ion flux integrated over magnetic pitch angle in the equatorial plane. The view is from above the north pole [from Burch et al., 2001a].*

The right-hand panel of **Figure 9** is an RPI plasmagram; the magnetospheric analog of an ionogram. A plasmagram is a plot of echo amplitude (color scale) as a function of frequency and echo delay (x and y axes). The echoes labeled 1 are direct echoes from the plasmasphere below the spacecraft. These echoes are very diffuse, coming from irregularities that exist in these regions. A family of echoes labeled 2, 3 and 2+3 are all ducted echoes. From ray tracing analysis and echo direction measurements, the lower left-hand panel shows the corresponding directions of the ducted echoes. Path 2 echoes return to the spacecraft after reflecting at high northern latitudes. Path 3 echoes follow the flux tube and reflect in the southern hemisphere, while path 2+3 are echoes that first reflect in the northern hemisphere, then propagate all the way to the southern hemisphere and

Surprising new results from RPI observations reveal the density structure of the plasmasphere along refilling flux tubes.

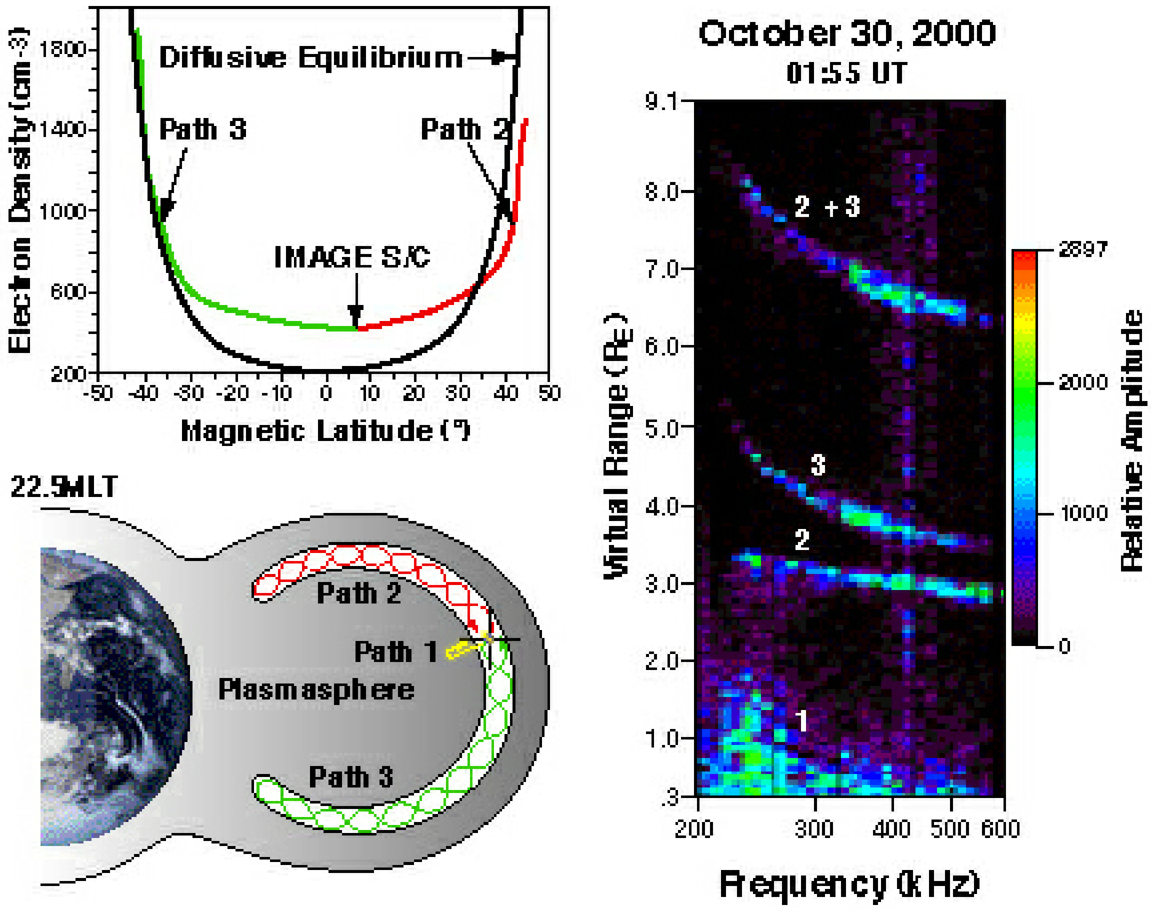

Figure 9. *Analysis of field-aligned or ducted echoes from RPI provides information on magnetic field line length and the electron density profile along the field line [Green, 2000].*

return to the spacecraft. The characteristic shape of the echoes in the plasmagram are sensitive to the electron density distributions along the field line. The ducted echoes of **Figure 9** have been inverted to reveal the field-aligned density structure of the plasmaspheric filling regions. The corresponding density profiles (from paths 2 and 3) are shown in the upper left portion of **Figure 9**. The density profile obtained from this analysis deviates significantly from diffusive equilibrium and shows plasma accumulation along the field line at high altitude. In addition, the plasma in this flux tube is not symmetric about the magnetic equator. At this time, these observations tilt the balance toward the top-down plasmaspheric filling model. However, even that model does not accommodate the observed asymmetry. A more detailed analysis of plasmaspheric ducted echoes is in progress.

4. FUV Imaging of Electron and Proton Auroral Substorms. FUV data presented by *Mende et al.* [2001b] show the development, during the expansive phase of a substorm, of a double oval configuration, consisting of a set of discrete poleward forms and a separate equatorward diffuse auroral oval. A simultaneous FAST pass provided a diagnostic of the particle types in the various regions. From these data, it was seen that in the last part of a substorm expansive phase and the following recovery phase the auroral oval had five components in order of decreasing latitude: a) active (convecting) irregular forms inside the polar cap and near the polar cap/auroral oval boundary, b) a region of discrete auroras consisting mainly of arcs, c) a gap consisting of lower precipitation intensities, d) a region of diffuse auroras with occasional structure embedded, and e) a region of proton auroras overlapping and slightly equatorward of the diffuse aurora. The auroras deeply inside the polar cap, and

Correlations between FUV auroral images and FAST plasma measurements identify a distinct latitudinal structure of auroral acceleration processes during a substorm.

at the poleward edge of the auroral oval, were very active and dynamic. The presence of this auroral activity calls into question the existence of a distinct polar cap boundary, which has been used to characterize the activity level of the magnetosphere [*Brittnacher et al.*, 1999]. The simultaneous electron observations from FAST also showed the dual auroral situation. The low-latitude region shows mainly diffuse precipitation. There is a gap, and poleward of the gap are high intensity, electrostatically accelerated electrons. Immediately poleward of these electrons, another group of electrons are seen with broader energy spectra characteristic of wave-accelerated particles. These electrons were presumably accelerated by the substorm dipolarization process. Therefore, the poleward arc feature, seen brightly by the IMAGE satellite, represents the poleward boundary of the inverted-“V” type electrostatically-accelerated electrons, and the substorm-associated acceleration region was seen as a weaker feature located poleward of the bright arc. These findings need to be verified by several more case studies because they would radically change our current understanding of the substorm process.

5. Role of Wave-Particle Interactions in Ring Current Decay. Simultaneous imaging of the ring current with HENA and of the plasmasphere with EUV has made it possible to study the spatial relation and interaction between the two plasma populations and is providing important information about the processes involved in ring current decay. Initial analysis of HENA and EUV images acquired during the magnetic storm of 24 May 2000 [**Figure 10**] suggested that significant ring current ion precipitation occurs near dusk, resulting from the interaction of the hot ring current plasma with the cold plasmaspheric plasma [*Burch et al.*, 2001b]. A more recent study using HENA observations from the 24 May storm, together with correlative EUV images and particle data from the Polar and NOAA/POES spacecraft, indicates that low ENA fluxes observed at higher energies (above 27 keV) in certain local

HENA-EUV correlations support theory of wave-particle interactions as a ring-current loss process.

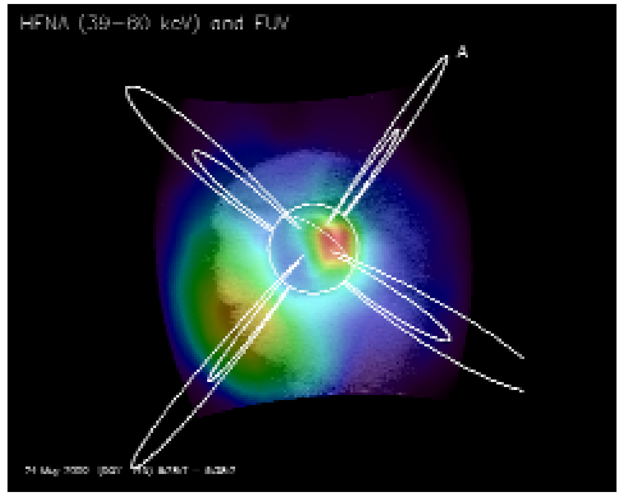

Figure 10. *Superposition of a HENA ring current image (false color) on an EUV plasmasphere image (blue-white scale) shows the spatial relationship between the two plasma populations. The view is toward the north pole; the limb of the Earth and the terminator are drawn in the center of the image. The dipole field lines at L=4 and 8 at local noon, dusk, midnight, and dawn are also shown. Local midnight is toward the upper right (denoted by A). In the morning to noon sector, the ring current peak follows the plasmapause and decreases inside the plasmasphere. The lack of ENA emissions in the dusk sector is likely due to precipitation of ring current ions resulting from interaction with the cold plasmaspheric plasma [Burch et al., 2001b].*

time sectors are due to ring current ion pitch-angle distributions (PADs) that are peaked at 90° and that result in fewer ENAs being emitted toward the detector [**Figure 11**] [*Brandt et al.*, 2001a]. The low ENA fluxes are associated with regions of high plasmaspheric density (as determined with EUV), which suggests that the PADs are modified by the plasmasphere/ring current interaction. It has long been recognized that when hot plasma of the ring current overlaps the cold plasma of the plasmasphere waves can be generated that change the PADs of the ring current ions [*Cornwall et al.*, 1970; *Williams and Lyons*, 1974; *Taylor and Lyons*, 1976]. Accordingly, Brandt et al. propose that ion cyclotron waves excited by the interaction of the plasmaspheric and ring current ion populations are, in part, responsible for the peaked PADs apparently associated with regions of high plasmaspheric density. Changes in the PAD may also result, in part, from conservation of the adiabatic invariants as the ions drift in to lower L shells (and higher magnetic field strength).

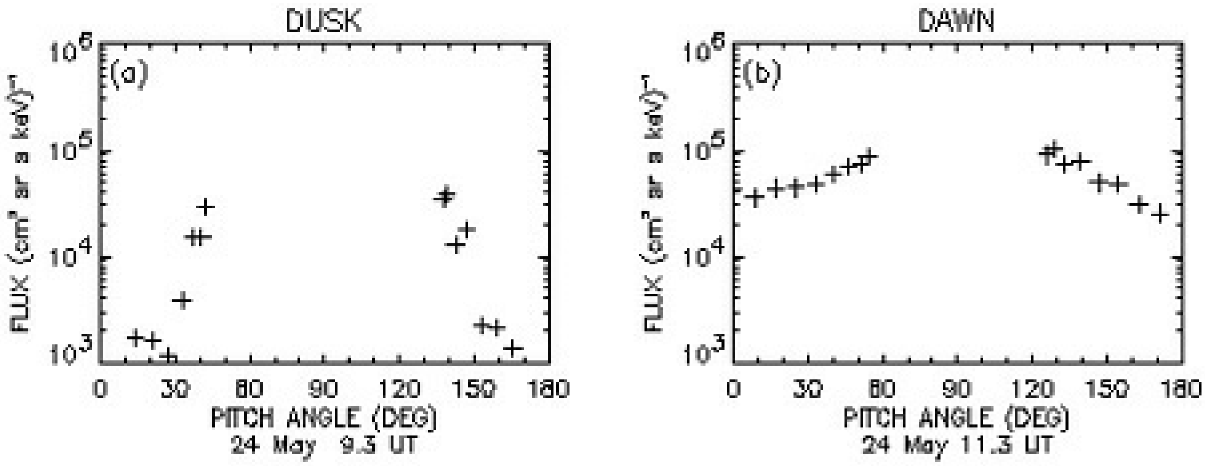

Figure 11. *Polar in-situ measurements of ring current ions on 24 May show strongly peaked pitch-angle distributions in the dusk sector and more isotropic distributions in the dawn sector. The anisotropic distributions are associated with regions of high plasmaspheric density [Brandt et al., 2001a].*

6. Proton Precipitation Associated with the Plasmaspheric Tail. It is now known that the plasmaspheric tail extends to the duskside magnetopause [*Burch et al.,* 2001a] and that the hot proton population has its largest anisotropy in this region [*Brandt et al.,* 2001a]. When the magnetopause is compressed by a solar wind impulse (such as a CME shock), the hot plasma anisotropy increases. In the region where the cold plasma density is high, the proton cyclotron instability threshold is low, and plasma in this region has the highest probability of going unstable [*Williams and Lyons,* 1974]. In reducing the free energy source, ion cyclotron waves scatter energetic (several keV) protons into the loss cone, causing enhanced precipitation. The bottom panel of **Figure 12** represents the effect of this precipitation following a solar-wind pressure pulse [*Fuselier et al.,* 2000a]. The proton aurora image from FUV SI12 shows the auroral oval (12 LT is in the lower left hand corner of the oval) and a second region of precipitation that is equatorward of this oval. This second region is the foot point of the plasmaspheric tail. Mapping the proton aurora image along the magnetospheric field lines to the equator shows that this region of enhanced precipitation maps to the duskside equatorial magnetopause (upper panel of **Figure 12**). Simultaneous in-situ measurements from a Los Alamos geosynchronous spacecraft (not shown) indicate the presence of a region of dense, cold plasma in the region to which this proton precipitation maps. This new precipitation feature is another manifestation of the cold-plasma induced loss of ring current plasma as it convects around the dayside.

D. Heliospheric and Interstellar Neutral Atoms

One of the science goals of the IMAGE mission was to search for solar and interstellar neutral atoms, neither of which has ever been directly observed in the inner solar system (although interstellar He was observed from the Ulysses spacecraft). With the LENA instrument, IMAGE has succeeded in detecting both neutral populations (**Figure 13**). Solar neutrals may provide the potential for advance warning of coronal mass ejections (a few hours), while interstellar neutrals represent a way to remotely sense the galactic environment outside the solar system.

1. Solar Wind Neutral Atoms. Because of its excellent UV rejection, the LENA imager can detect neutral atoms coming from the solar direction [*Moore et al.,* 2001, Plate 1; *Collier et al.,* 2001]. These neutral atoms are created by the exchange of charge between solar wind protons and exospheric hydrogen. The imager sees a weak, diffuse peak when the Sun is outside of its field of view and a sharp, intense peak when the Sun is within its field of view. The two different responses are the result of a difference in the Mach number of magnetosheath plasma compared to that of the upstream solar wind. (Fluxes very similar to those observed with the LENA imager have been produced in a simulation

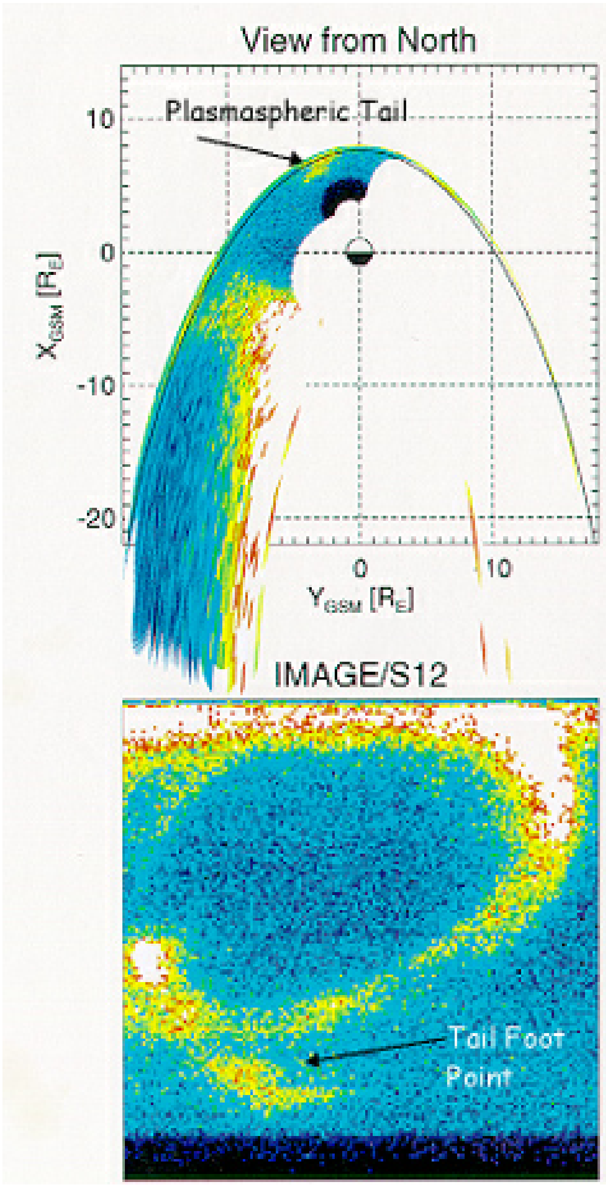

Figure 12. *FUV proton aurora image (bottom) is mapped to the equatorial plane using the T96 magnetic field model (top) [Fuselier et al., 2000a].*

of the LENA response to the neutral solar wind created by charge exchange with the Earth's exosphere.) Because the fast solar wind neutrals are not affected by the Earth's magnetic field, they provide a potential means of monitoring solar wind intensity from a vantage point inside the magnetosphere.

Solar wind neutrals are also created by charge exchange between the solar wind and interstellar neutrals. LENA data have revealed that the solar wind neutrals had a pronounced long-term variation over the first nine months of the mission. This variation represents an azimuthal variation of the integral neutral gas density between the Sun and Earth and is loosely aligned with the known direction of motion of the solar system through the galaxy. These observations of seasonal variations in the neutral solar wind component appear to be related to charge exchange of the solar wind with interstellar neutrals, which creates fast solar wind neutrals and interstellar ions. Analysis of these findings is still in progress but has the potential to yield information about the distribution of gas in the inner solar system.

2. Interstellar Neutral Atom Sensing. IMAGE has also directly observed the interstellar neutral atoms as the spacecraft was passing beyond the anti-apex direction downstream in the galactic gas flow. The weak signal, which we predicted would be detected beginning on 7 December 2000, actually appeared about 25 December 2000 and disappeared about 8 February 2001. The delay was due to masking by the solar wind neutral component. It was narrow in angular distribution and centered on the ram direction of the Earth's motion around the Sun (**Figure 14**). The appearance and disappearance of the direct interstellar neutrals in the LENA imager is closely associated with the field of view of the imager and the bending of interstellar neutral trajectories as they pass through the gravitational field of the Sun. Our study of this direct interstellar neutral signal, like that of the solar wind neutrals, is just beginning. However, the detection of these neutrals in the inner solar system holds promise for future studies of the interstellar medium from the near-Earth environment.

LENA made the first observations of charge-exchanged solar wind and interstellar neutral atoms from inside the magnetosphere.

E. IMAGE Education and Public Outreach

The IMAGE E&PO effort is a major effort of the entire IMAGE team. Many team members have been involved in creating and distributing images in a timely fashion to the community. The web sites at GSFC, SWRI, and Rice have been major sources of information and images to the public. The major articles on IMAGE in *Scientific American* and in *Science* have reached millions. “The Fury of Space Storms” Distinguished Lecture is available using “Realvideo” over the Rice webcast server (http://www.rice.edu/webcast). Even at the earliest stages of the IMAGE proposal, however, a specific

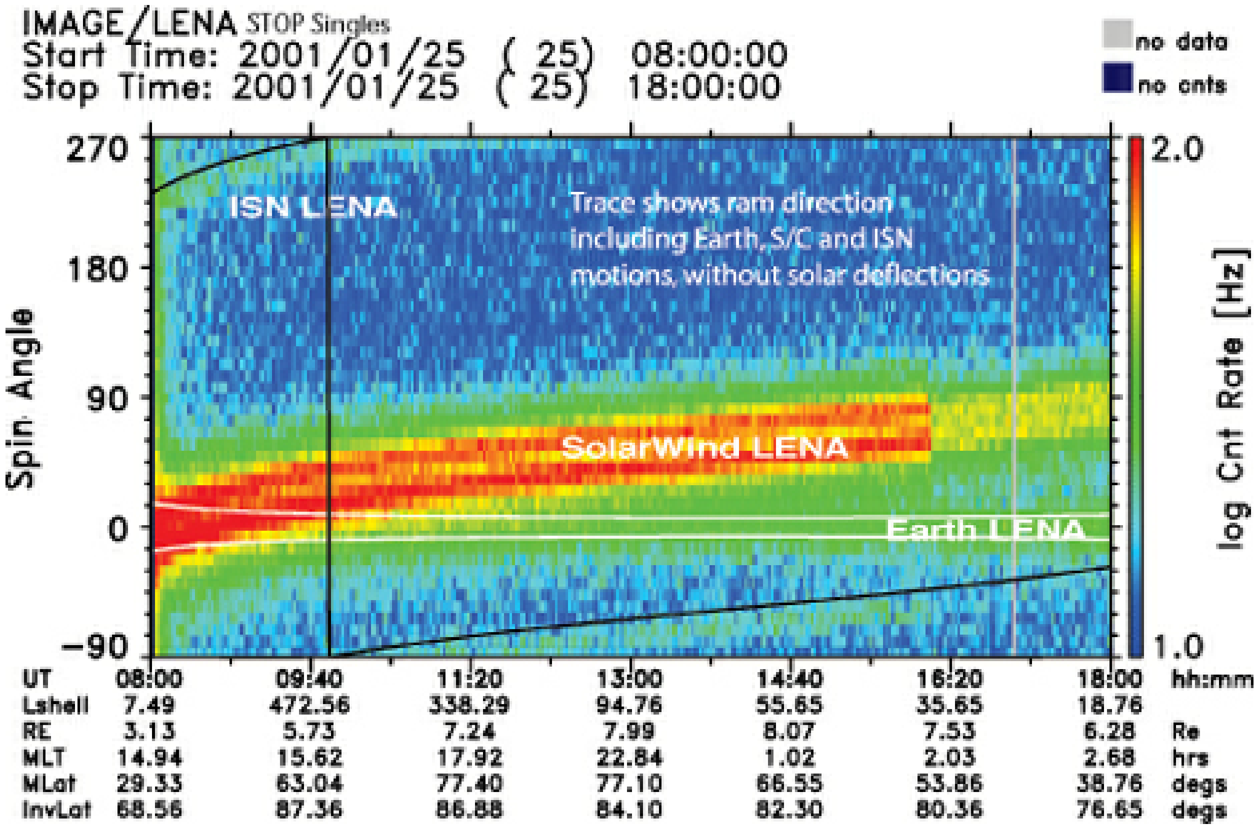

Figure 13. *Neutral atom fluxes from the Earth (charge-exchanged ion outflow), the solar wind (charge-exchanged solar wind ions), and the interstellar medium (interstellar neutrals). The interstellar neutral signal comes from a direction that is the vector sum of the Earth's velocity vector around the Sun and the bent trajectories of the neutrals as they pass through the gravitational field of the Sun [Burch, 2001b].*

plan for outreach and a specially-funded team was brought together to involve both formal education (K-12 and college student), and informal education - via museums and science centers. The "POETRY" group (Public Outreach, Education and Training, Reaching Youth) has developed much-needed basic resources for K-12 teachers so that they could tell the story of space weather and its invisible geomagnetic impacts. The team established a network of collaborating schools and museums, and IMAGE is now recognized as one of the most innovative and enthusiastic SEC missions in working with the NASA/OSS Sun-Earth Connection Education Forum (SECEF). Specific achievements of the IMAGE team fall into two categories: K-12 Education and Public Outreach. The POETRY web site can be found at http://image.gsfc.nasa.gov/poetry/ or at the GSFC and SwRI IMAGE web sites (http://image.gsfc.nasa.gov/ and http://pluto.space.swri.edu/IMAGE/, respectively.)

1. K-12 Education. The POETRY team developed five K-12 education products including two lithograph sets and five NASA Educator Guides. We collaborated in the development of the *Blackout!* curriculum module which is currently distributed by Addison-Wesley and available to all teachers. The module includes workbooks, a CD-rom, and an overview video. These workbooks were the first ones developed for NASA that featured mathematical problems in space science and have gone on to become exemplary educational resources for NASA. POETRY has also conducted numerous teacher workshops at the National Science Teachers Association and the National Council of Teachers of Mathematics conventions, at NASA Goddard and through the Maryland Department of Education, reaching over 600 teachers. The NASA/OSS SECEF commissioned POETRY to write and produce a set of 10 lithographs that highlight the major elements of Sun-Earth Connection science. This set will be distributed to 25,000 teachers in 2001 and will be leveraged by NASA into a much larger printing in 2002-2003.

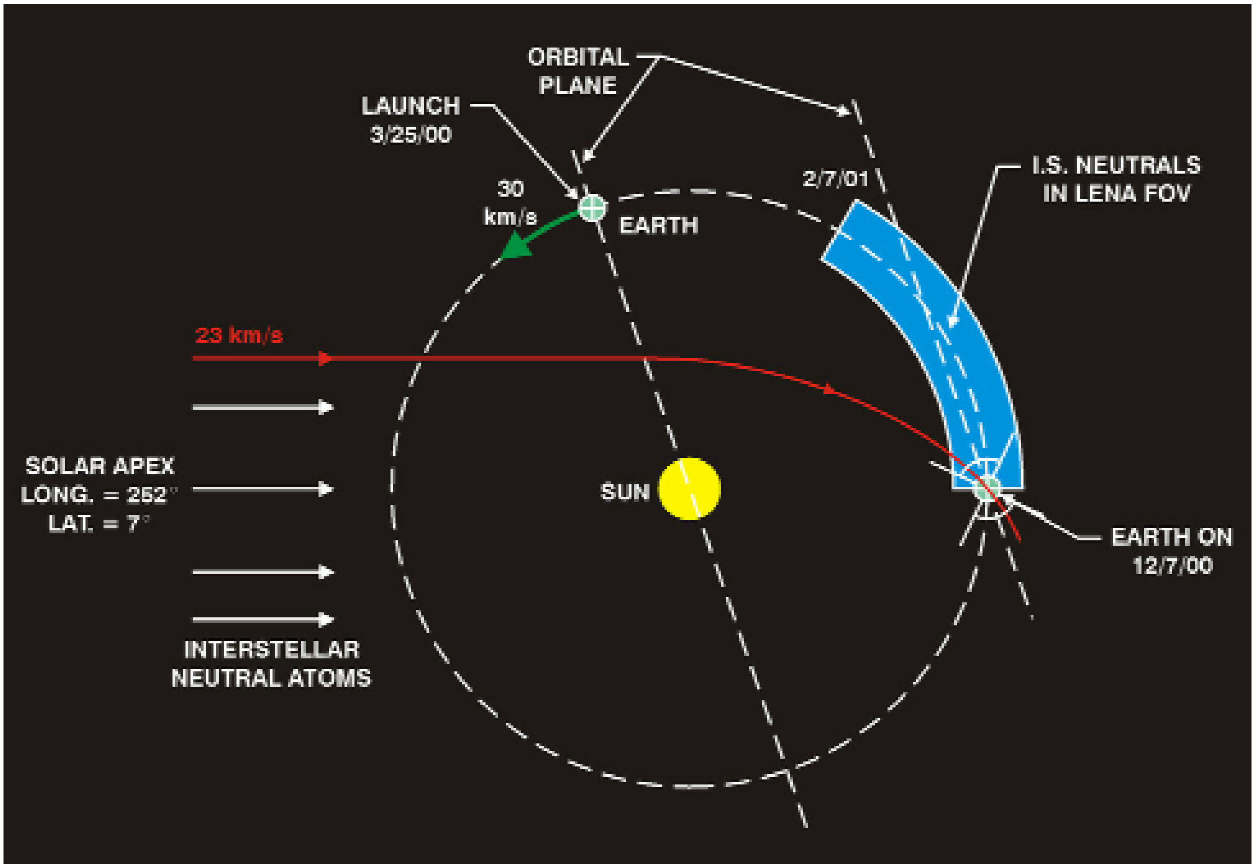

Figure 14. *Interstellar neutral atoms were predicted to move into the field of view of LENA for two months beginning in early December 2001. Owing to masking by the solar wind neutrals, the signal was not actually observed until 25 December 2001. The red trace shows the trajectory of the neutral atoms through the inner solar system as modified by solar radiation pressure and gravity. The orbital velocity of the Earth (30 km/s) is comparable to that of the interstellar atoms (23 km/s) [Burch, 2001b].*

The "POETRY" CD-Rom, which includes all of the resource material on the POETRY site and the GSFC and SWRI IMAGE sites, and also the "Exploration of the Magnetosphere" web module, was distributed to 10,000 teachers and museum educators in 1999-2000. Chosen as one of only two Sun-Earth CD's to be distributed at major teacher meetings, it was updated as the "IMAGE" CD (**Figure 15**) in summer 2000 (in time for the summer NSTA and AAPT meetings). Version 4 was completed in November, 2000, with 20,000 printed. Of this, over half have been distributed at teacher and museum meetings so far in 2001.

POETRY sponsored the IMAGE, First Annual Aurora Essay Writing Contest at an Alaska elementary school; student essays from this contest will be featured on a poster currently under development. IMAGE has also continued its close relationship with the INSPIRE program of high school-level VLF radio observations, now conducted by over 1700 participants nationally. POETRY also added a second program, the Student Magnetometer Network (MagNet), in which networks of schools use our $5.00 soda bottle magnetometer to track magnetic storms. This network includes 25 schools in the Chicago school district, and a new network of schools in the United Kingdom.

2. Public Outreach. Lockheed, UC Berkeley, and SwRI have collaborated on the production of an "Auroral Storm" poster showing IMAGE's view of the "Bastille Day" aurora. 15,000 copies have been printed and will be distributed to educators and

> *"The [IMAGE] solar storms lesson plan/workbook produced last year was an excellent example of Space Science getting to the real customers… the future generation of scientists and engineers."*
>
> *E.J. Weiler*
> *NASA Associate Administrator*

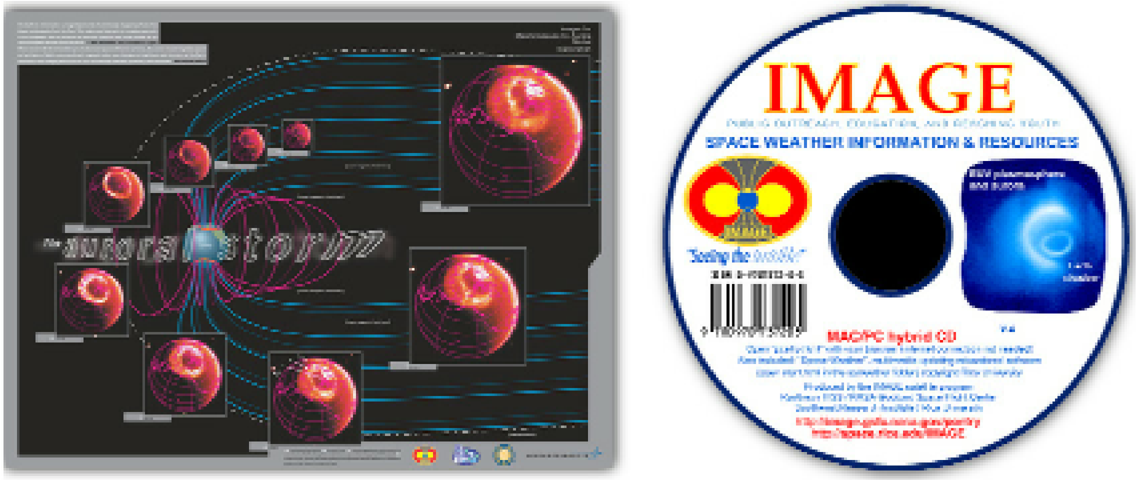

Figure 15. *The IMAGE team has developed a variety of resources for K-12 education and public outreach, including the "Auroral Storm" poster and the IMAGE CD-ROM, of which more than 10,000 copies have so far been distributed to teachers and museums in 2001.*

interested members of the general public (**Figure 15**). The POETRY team developed an award-winning web site that features an "Ask the Space Scientist" resource, which answers 6000 questions per year from students, teachers and the general public. One of the team leaders authored the Columbia University Press *The 23rd Cycle* book on solar storms and their human impacts [*Odenwald*, 2001]. IMAGE science was also featured in the first annual "Sun-Earth" Day (28 April 2000), which brought solar science to a new generation of learners. Rice created a 3-minute movie explaining space weather to the public for this year's exhibition. This movie will be available on the IMAGE web sites, and on the next version of the IMAGE CD-Rom.

The most exciting new educational venue is immersive digital theater, displayed on the inside of a planetarium dome. We have developed the world's first fulldome space weather show, "Force 5," which opened at the Carnegie Museum of Natural History in December 2000, and which will open in Houston in June 2001. Audiences see a larger-than-life-size IMAGE spacecraft on orbit, are buffeted by a major CME, and experience the Earth's response. Segments of that show will be included in other planetarium shows around the world and offered as HDTV segments for space weather TV shows.

3. Recognition. The IMAGE team's E&PO efforts and products have been widely recognized for their excellence and innovation and have received numerous awards. Most recently, Dr. Edward J. Weiler stated in an email: "The [IMAGE] solar storms lesson plan/workbook produced last year was an excellent example of Space Science getting to the real customers... the future generation of scientists and engineers. Living With a Star would have NEVER been funded if the solar/space physics mission science teams and the EPO people who work with them didn't get their exciting science out to the public. I have NO doubt in my mind that the EPO effort of the past two years played the pivotal role in awakening the media and the public to the importance of space weather and the effects of the sun. I was so thrilled with the [IMAGE] workbook/lesson plan that I personally handed a copy of it to a Congressman on the House Science Committee who shows special interest in what NASA does for education."

Awards received by the IMAGE team for its E&PO activities include two Telly Awards and a Crystal Award for *Blackout!*, the GSFC Excellence in Outreach Award (May 2001), and the RITSS E/PO Award for 2001.

II. THE CONTINUING PROMISE OF IMAGE: RECURRENT STORMS AND THE CHANGING IMAGING PERSPECTIVE

A. New Mission to 2005

The scientific accomplishments of IMAGE to date have opened the door to many new scientific discoveries. Beyond the prime mission, the progression through the solar cycle and the precession of the IMAGE orbit will provide the opportunity for an essentially new mission for IMAGE during the years 2002 through 2005. The focus of the new mission will be on the recurrent magnetic storms associated with high-speed solar wind streams and corotating interaction regions.

During the two-year prime mission of IMAGE, the apogee, and hence the primary imaging perspective, will remain above the northern polar cap. However, the relatively rapid precession of the 90-deg. inclination orbit will cause the imaging perspective to evolve through low latitudes and into the southern polar cap during a three-year mission extension ending in 2005 (**Figure 16**). While the high-latitude perspective provides full local-time imaging of magnetospheric plasmas, the ENA emissions from that perspective are often dominated by low-altitude sources because of higher exospheric densities and field-line convergence. A mid to low-latitude imaging perspective, on the other hand, will complement the prime mission by allowing imaging of the field-aligned distribution of the ENA emissions. A similar consideration applies to EUV imaging of the plasmasphere. Other significant features of a lower-latitude apogee include the ability to image the aurora with FUV and the ionospheric outflow with LENA with higher spatial resolution and in both hemispheres in the ascending and descending parts of the orbit. Finally, with apogee at low latitudes on the day side, RPI will have its best opportunity to sound the magnetopause and track its motion.

New IMAGE Mission (May 2002 - 2005)
Provides opportunity to investigate recurrent magnetic storms
Provides new imaging perspectives (low-latitude and southern hemisphere)

In addition to the changing imaging perspective, IMAGE will benefit from the epochal change in solar activity that it will experience during the extended mission. As time progresses from 2002 through 2005, magnetic activity will in general wane, but the mostly CME-driven storms of solar maximum will be replaced by the smaller, but possibly even more frequent, recurrent storms that typically occur during the declining phase of the solar cycle in association with coronal holes [*Tsurutani et al.*, 1995]. The specific studies described in the following sections build on new knowledge gained from the IMAGE prime mission and particularly on its highly integrated theory program.

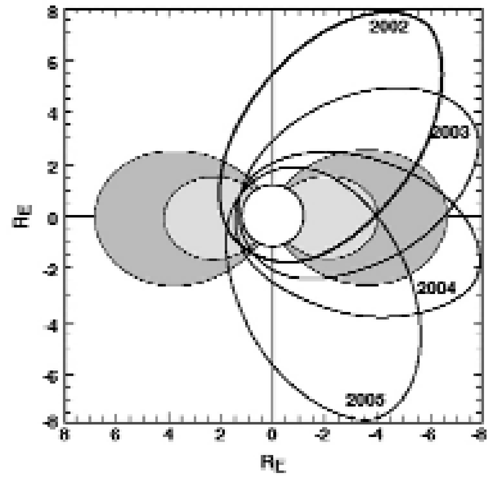

Figure 16. *From March 2002 to March 2005 the IMAGE line of apsides will precess from high northern latitudes to high southern latitudes. Orbits are plotted in the orbit plane in which right ascension = 12º(left half) and 192º (right half). The local time precession is not shown since the 90º-inclination orbit is fixed in inertial space.*

1. Solar Cycle Dependence of Ionospheric Outflow. IMAGE has shown that there is a prompt ionospheric outflow in response to input from the solar wind [*Fuselier et al.*, 2001]. This prompt ionospheric outflow is the result of energy input into the topside ionosphere near the oxygen scale height. These observations were made during solar maximum when the exosphere is relatively hot and the oxygen scale height is high.

It is well known that the ionospheric outflow is solar-cycle-dependent. However, it is not known how (or indeed if) this dependence is a result of changes in the relative importance of various energization mechanisms that accelerate oxygen to escape velocities. In the declining phase of the solar cycle, the exosphere is expected to cool, the oxygen scale heights should drop, and the H density should increase. The net result of these effects may be an observable delay between the time of arrival of an ionospheric disturbance (such as a high-speed solar wind stream associated with a co-rotational interaction region) and the outflow observed by LENA. This delay could signal a change in the relative importance of various energization mechanisms. The lack of an observed delay would effectively eliminate certain acceleration mechanisms or at least severely reduce their importance.

2. Magnetic Field-Aligned Plasma Dynamics. In the 2003-2004 time frame the IMAGE spaccraft, as shown in **Figure 16**, will have its apogee at low latitudes. It is during this phase of the mission that a unique opportunity will exist for the IMAGE spacecraft to make a variety of global observations while moving nearly along a constant L shell. This configuration will allow observations of plasmaspheric refilling and changes in magnetic field-line lengths during substorms.

3. Dynamics and Structural Changes of the Magnetopause and Cusp. Based on in-situ measurements in and around the magnetopause acquired over long periods of time, two views of solar wind plasma entry into the magnetosphere have emerged. It is believed that reconnection produces abrupt gradients within the magnetopause boundary layer while diffusive processes lead to generally smooth density gradients. During its extended mission, IMAGE will approach the magnetopause more closely than at any other time. Owing to the high magnetosheath plasma densities at the subsolar point (four times that of the solar wind), RPI will be able to probe the magnetopause boundary layer at higher frequencies where the instrument is more efficient. In addition, RPI will be able to determine the location of the magnetic equator from the ducted echoes coming from each hemisphere and the plasmapause from the direct echoes (see **Figure 9**).

4. Cusp Plasma Injection. Recent studies of the cusp indicate that it can be modeled either by plasma entry through quasi-steady reconnection or by pulsed reconnection [*Fuselier et al.*, 2000b; *Lockwood and Smith*, 1992]. IMAGE has shown conclusively that FUV can image the proton precipitation at the cusp foot point (**Figure 2**) and that RPI can image the cusp [*Reinisch et al.*, 2001]. During the extended mission, there will be many intervals where RPI will be located on the dayside boundary between magnetospheric (closed) and cusp (open) field lines. Transition across this boundary will result in a readily observable switch from ducted echoes coming from both hemispheres to a single ducted echo. Furthermore, the decreasing distance to the cusp boundary will be measured by RPI imaging, and the length and density distribution along the field line will be determined once the spacecraft is in the cusp. These observations, combined with FUV imaging of the motion of the cusp foot point, will allow for the distinction between a true change in density along a cusp field line (i.e., a temporal change caused by pulsed reconnection) and simple motion out of or within the cusp (i.e., a spatial change caused by cusp motion). This resolution of temporal and spatial effects is critical to distinguishing between the two leading models of cusp formation.

5. Field-Aligned Densities and the Length of Closed Magnetic Field Lines over Substorm Time Scales. RPI measurements can be inverted and provide field line lengths in addition to the density profiles. During the extended mission, while on the nightside of the magnetosphere at mid-latitudes, observations of ducted echoes from RPI providing field line length can be combined with auroral observations from FUV to observe the topological change of the nightside magnetosphere during substorms. These measurements will be the first ones to correlate the auroral phases with measurements of stretching and dipolarization of magnetic field lines in the nightside magnetosphere.

6. Ring Current Pitch-Angle Distributions. The usefulness of equatorial views of the plasma sheet and ring current was pointed out by *Moore et al.* [1995]. They noted that the pitch angle distribution (PAD) determines the distribution of ENA brightness along the flux tube. Field-aligned, and even isotropic, pitch-angle distributions result in enhanced ENA brightness at the footpoints of magnetic field lines. On the other hand, pancake distributions (peaked near 90^o pitch angle) shut down the ENA brightness near the Earth. Thus, the general character of the PAD can be remotely sensed from the brightness distribution along a flux tube, which can be readily observed from low-latitude perspectives, as shown in the simulations in **Figure 17**. The evolution of PADs from field-aligned, to isotropic, and to pancaked, is a sensitive bulk indicator of the plasma loss rate during the evolution of substorms.

7. The Plasmapause in Perspective. The new IMAGE perspective on the magnetosphere should also be beneficial for plasmaspheric EUV imaging. As shown in **Figure 18**, numerous types of plasmasphere features are being observed from the polar perspective of the prime mission, including troughs, spokes, voids, detached flux tubes, shoulders, and the convection tails associated with erosion of the plasmasphere during storms [*Sandel et al.*, 2001]. Convection tails and detached plasma flux tubes had been inferred from in-situ measurements long before the IMAGE mission, which has used global EUV imaging to demonstrate the importance of convection tails. Recent modeling [*Goldstein et al.*, 2001] has produced a description of the shoulder

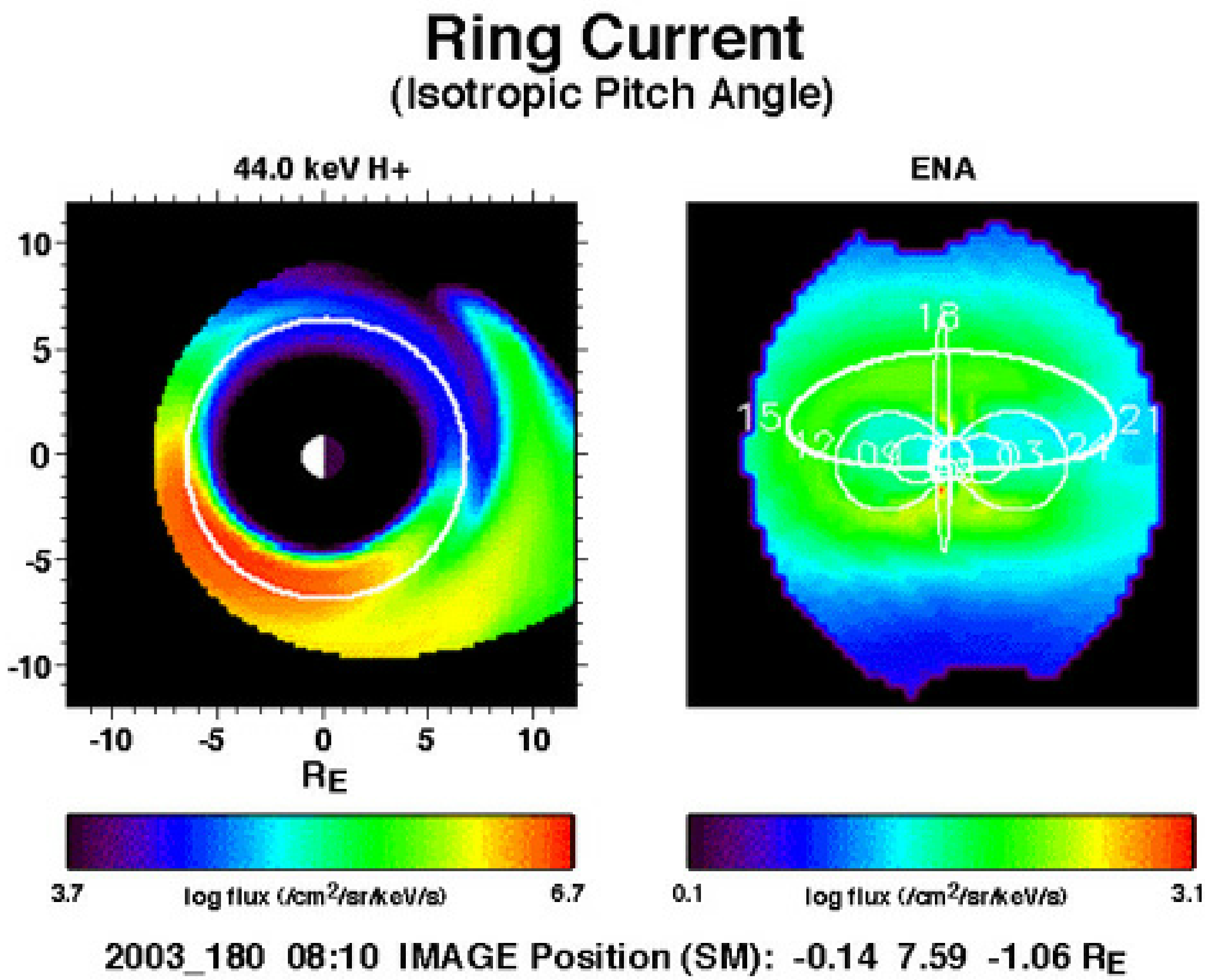

Figure 17. *Substorm injections by dipolarization of the plasma sheet field produce some field alignment of the resultant injected flux. The panel on the left shows the equatorial distribution of 8.6 keV protons, while the right-hand panel shows the computed ENA image as viewed from an equatorial perspective. The resultant brightness of the flux tube footpoint is readily apparent from the low-latitude perspective.*

formation during plasmasphere erosion and tail formation. However, the other unexplained features do not fit with any known description of plasmapause dynamics, and it is clear that viewing them from additional perspectives will contribute additional information and constraints of possible descriptions.

8. Plasmaspheric Refilling Dynamics. One of the outstanding problems in plasmaspheric dynamics that can be studied effectively by imaging from a low to mid-latitude perspective is the physics of the refilling process. Classic models of the outflow of ionospheric plasma describe the refilling of the plasmasphere after erosion by storms as a hydrodynamic process involving either a single fluid or separate fluids from each hemisphere [see *Singh and Horwitz*, 1992]. These models predict that the outflow streams from the two conjugate hemispheres will interact strongly as they meet at the equator, forming a dense wedge of plasma there, bounded by at least two hydrodynamic shocks that propagate back toward the conjugate hemisphere. In contrast to this “top-down” model of plasmaspheric refilling, kinetic models of this process [*Wilson et al*., 1992; *Lin et al.*, 1992] predict that the two streams can, under typical circumstances, pass through each other collisionlessly, producing no equatorial density peak or propagating shocks (the “bottoms-up” refilling model). The difference between these two models is readily visualized in EUV imagery of the plasmasphere, as shown by simulation in **Figure 19**.

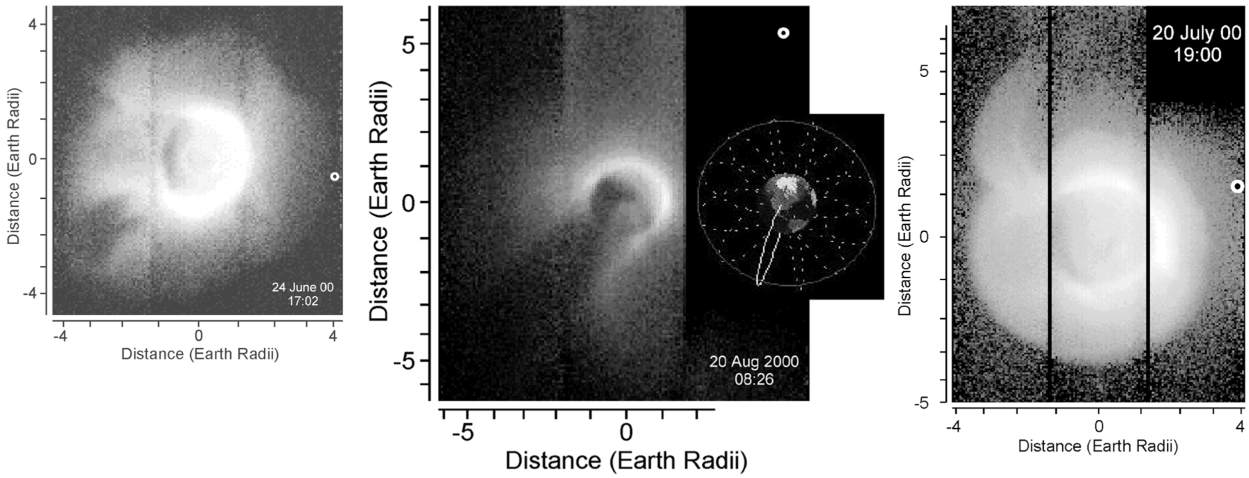

Figure 18. *EUV imaging has revealed both familiar and confounding features of the plasmasphere. These panels show examples of voids and spokes, detached flux tubes, and a plasma tail that agrees qualitatively with the classic Grebowsky [1970] model of such tails. The images are taken from Sandel et al. [2001].*

As shown in **Figure 19**, a unique opportunity to resolve the outstanding questions surrounding flux tube refilling will be afforded by extended operation of the IMAGE spacecraft. By 2003, its apogee will have precessed to the vicinity of 30º latitude. From this vantage point, magnetic flux tubes previously emptied by storm-time convection can be observed during early refilling times as they convect through dawn and into the morning. At the same time, as the region of accumulating plasma reaches downward toward the ionosphere, the densities in the trapped region also increase. Orbit by orbit and for hours at a time, EUV images will document all stages of refilling and clearly distinguish between the models.

The low-latitude apogee (2003-2004) will provide a unique opportunity to image plasmasphere refilling.

Another opportunity for the remote measurement of plasmasphere refilling will be afforded by RPI sounding during the extended mission. One of the new results from RPI is that ducted echoes are observed when density irregularities occur along the plasmaspheric flux tubes that are filling. Currently, the IMAGE orbit cuts through the outer plasmasphere and trough regions, making observations of ducted echoes possible only over a time period of 10s of minutes, resulting in only a handful of plasmagrams with ducted echoes. However, during the extended mission phase IMAGE will spend several hours moving through only a few L values. The expected results during this configuration can be simulated. **Figure 20** is a ray tracing simulation of two ducted echoes along a field-line and their associated field line length and density distributions. **Figure 20** shows the density profiles (label A for a diffusive equilibrium model and B for a non-diffusive equilibrium model) with a symmetric increase in density starting from the equator. The characteristic echo structure in these plasmagrams is found to be sensitive to the density distribution and field-line lengths. Repetitive measurements by RPI during the extended mission phase will be used to determine the mechanism of plasmaspheric filling and provide clear time sequences of events. These measurements will be important to provide a context for the EUV plasmaspheric measurements, which will be made around apogee providing full profile views of the plasmasphere.

9. High-Resolution Ionospheric Imaging. As shown in **Figure 16**, during 2003 and 2004 the IMAGE apogee will be at low latitudes. In this configuration, LENA and FUV will be able to acquire high spatial-resolution images of the ionospheric outflow and the aurora on the upleg and downleg of each orbit. The auroral imaging during this time will provide the opportunity for higher fidelity comparisons of auroral arcs with in-situ particle measurements from FAST or other low-altitude spacecraft. In addition, simultaneous imaging with FUV and

The low-latitude apogee (2003-2004) will provide high spatial-resolution imaging of ionospheric outflow and the aurora in both hemispheres.

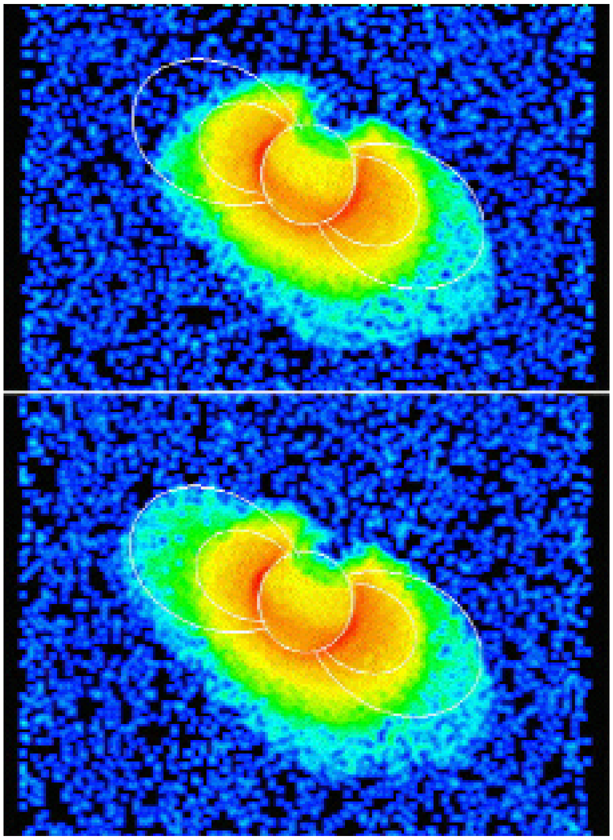

Figure 19. *Simulated refilling of dawn sector outer plasmaspheric flux tubes after subsidence of a magnetic storm as observed from a 28°-latitude perspective by the EUV imager. The top panel shows an initial state with depleted outer plasmasphere, while the bottom panel shows the same flux tubes during refilling. According to this model, a denser equatorial region is bounded by steep shock waves that are in the process of propagating from the equator along magnetic field lines toward the ionosphere. The shocks are most visible to the left of the Earth, near the inner of the two magnetic field lines shown. This is a top-down refilling simulation in which the density in the equatorial region grows linearly with increasing MLT and expands in latitude range with increasing MLT. The color bar varies with the logarithm of density.*

LENA will provide the best opportunity for global correlations between the large-scale features of the aurora and the regions of outflow of ionospheric hydrogen and oxygen.

10. Correlations with Other Spacecraft. During the extended mission IMAGE will both contribute to, and benefit from, other spacecraft missions in the magnetosphere. IMAGE will provide critical extended auroral imaging that Polar will lose once its fuel is depleted, while Polar will provide important in-situ measurements of energetic ions for correlations with the IMAGE ENA images. Cluster ion measurements in the high-altitude cusp will provide valuable input information for analysis of the IMAGE-FUV proton aurora images just as FAST should continue to provide. The first TWINS spacecraft will be launched in early 2003, and for the following six months IMAGE will be in a good position to provide the second imaging location, thereby enabling stereo imaging with MENA before TWINS 2 is launched in 2004.

11. Heliospheric Physics. Although IMAGE is primarily a magnetospheric mission, the extended mission offers unique opportunities to observe and interpret heliospheric interactions.

a. Long-Term Sampling of the Neutral Solar Wind. It is clear from the initial results that monitoring the solar wind ENA flux provides a unique remote sensing measurement of the solar wind interaction with the neutral gas environment between the Sun and the Earth. In addition to the variation in the neutral solar wind flux that was related to changes in the solar wind density and dynamic pressure, a clear seasonal variation was observed during the first year of observation. This long-term variation appears to be consistent with models of the interstellar neutral H distribution expected in the inner solar system. The variation is shown as the oscillating curve in **Figure 21**. The envelope of this annual variation is the solar cycle dependence. In the model without dust in the inner solar system, the charge exchange with interstellar neutrals is high during solar maximum (year zero in **Figure 21**), and the variation between the minimum and maximum flux is three orders of magnitude. However, when dust is included in the model, the variation is only a factor of three. In the extended mission, IMAGE will make observations during the declining phase of the solar cycle, when the envelope of the seasonal variations in the flux has its greatest variation. The LENA observations of the neutral solar wind provide a unique discriminant for the interstellar gas distribution and the distribution of dust in the inner solar system. By comparing the seasonal and solar cycle variations, these observations will distinguish between models with and without dust and may provide an independent measure of the amount of dust in the inner solar system.

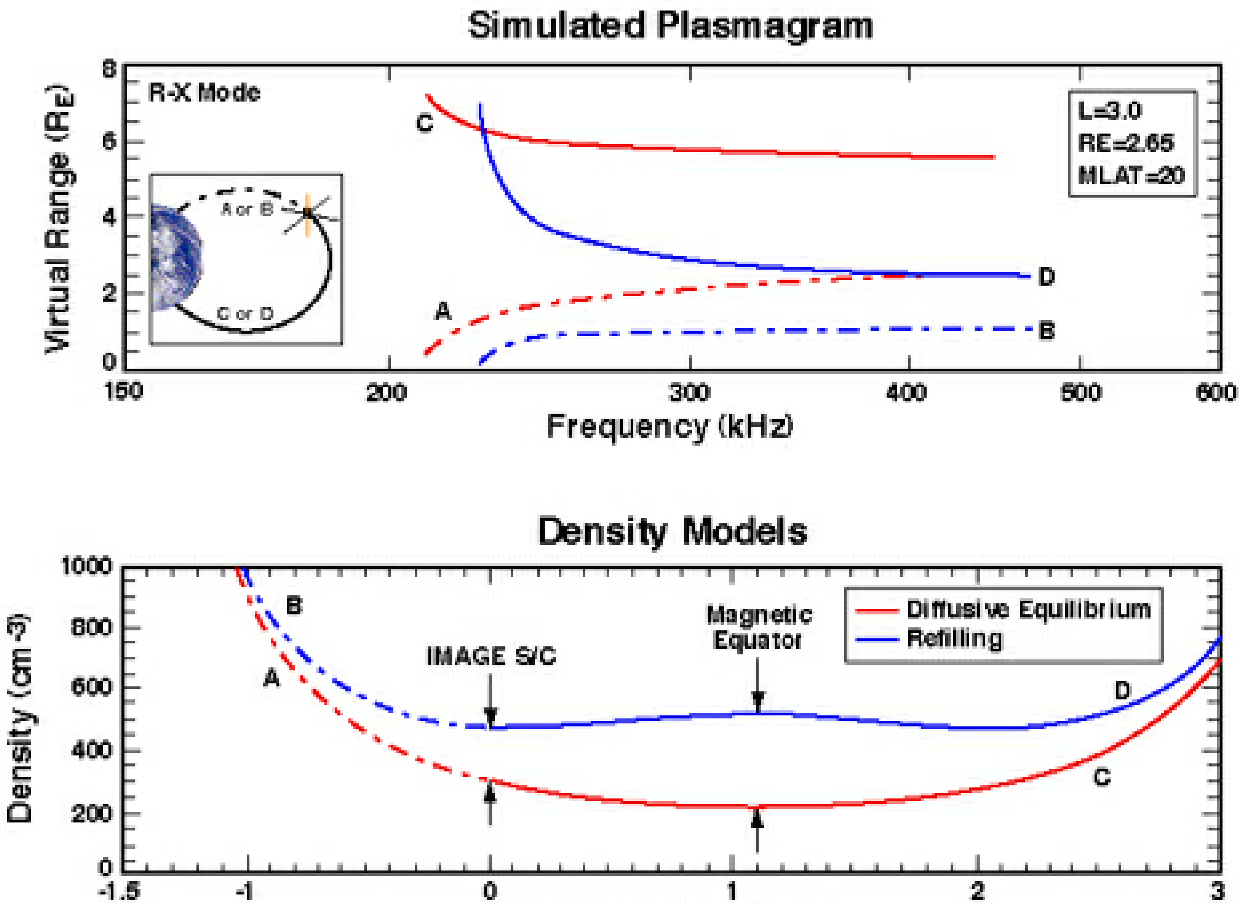

Figure 20. *Simulated RPI plasmagrams (top) associated with density models corresponding to diffusive equilibrium and plasmasphere refilling (bottom). The position of the IMAGE spacecraft is shown in the inset in the top panel.*

b. Interstellar Neutral Observations. During the first year of observations, a weak, direct signal of the interstellar neutrals arriving in the inner solar system was observed between late December 2000 and early February 2001 (cf. **Figures 13** and **14**). Interference from the neutral solar wind signal hampered determination of the exact dates when the neutral flux entered and exited the field of view of the LENA imager. These dates are important because they allow precise determination of the angular width of the neutral signal to a degree of accuracy much better than the 8˚ x 12˚ pixel size of the imager. Furthermore, the start and stop dates provide additional clues to the composition of the signal. In particular, the angular width and start and stop dates allow distinction between indirect detection of interstellar neutral He (which produces sputtered H^- ions in the instrument) and direct detection of interstellar neutral H.

In the extended mission, the background signal that hampered detection of the interstellar neutral signal will shift (owing to changes in the orbit apogee position) to allow a more precise definition of the dates when the interstellar neutrals are first detected and when they disappear from the field of view. By determining the angular width and start and stop dates (and ultimately the composition of the signal), the interaction of the interstellar neutrals with the heliosphere will be quantified. For example, current models of the interaction suggest that He interacts very weakly with the heliosphere, exhibiting a simple focusing cone on the downwind side owing to gravitational attraction by the Sun. In contrast, H interacts very strongly, possibly not producing any focusing cone. The LENA data will allow confirmation of these modeling results.

c. Interstellar neutral atoms from the termination shock. MENA and HENA have very low background count rates when they view in the anti-Earthward direction. During these times, they can search for energetic neutral atoms formed by the

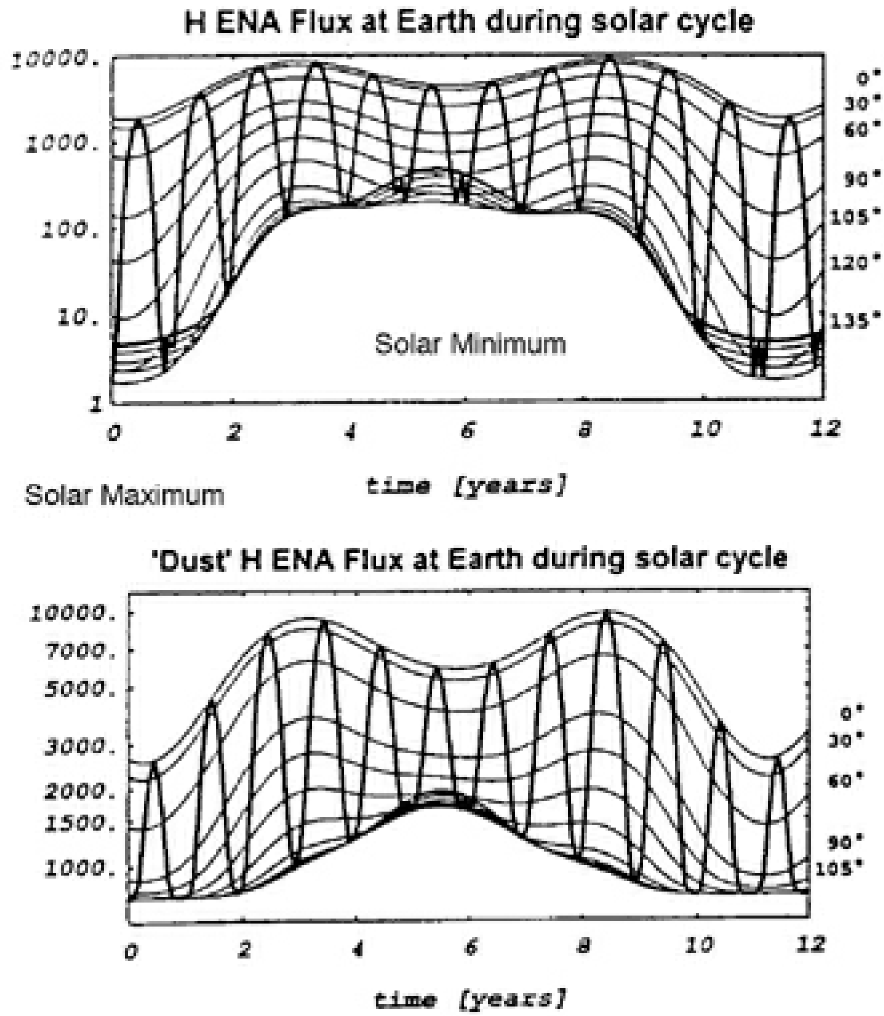

Figure 21. *Neutral solar wind flux variations over a solar cycle starting at solar max [Bzowski et al., 1996]. Oscillations are the annual variation, and the envelope shows the solar cycle variation. The top (bottom) panel shows the variation without (including) dust. Solar cycle dependences are expected to exceed a factor of 3, which is readi - ly observable by IMAGE/LENA and will constrain theories of the solar wind interaction with the inner heliosphere gas and dust.*

charge exchange of shock-accelerated solar-wind ions with interstellar neutral atoms. These particles contain information on the interaction of the solar wind with the interstellar medium. To date, only upper limits have been able to be placed on these fluxes, but as the mission proceeds, better statistics will be available, perhaps leading to drect measurements of this important population.

B. Significance of IMAGE to the Long-term Health of the Field

As evidenced by **Table 2**, IMAGE contributes to every goal of the NASA Space Science Enterprise 2000 Strategic Plan. There is strong representation in each of the enterprise goals, and IMAGE contributes significantly to 70% of the enterprise objectives

IMAGE has several important components that are critical to the health of the field.

- *IMAGE is the first "Space Weather Satellite" and is the only mission to obtain global multi - spectral images of the inner magnetosphere on time scales of a few minutes, which are relevant*

Enterprise Goals	Enterprise Objectives	IMAGE Contribution
Chart the evolution of the universe from origins to destiny and understand its galaxies, stars, planets, and life	Science Objectives •Understand the structure of the universe, from its earliest beginnings to its ultimate fate	
	•Explore the ultimate limits of gravity and energy in the universe	
	•Learn how galaxies, stars, and planets form, interact, and evolve	•Global imaging of the interactions between the Sun and the magnetosphere •Determination of long-term variation of interstellar neutral atoms; search for energetic neutral atoms from termination shock
	•Look for signs of life in other planetary systems	
	•Understand the formation and evolution of the Solar System and Earth within it	
	•Probe the origin and evolution of life on Earth and determine if life exists elswhere in our Solar System	
	•Understand our changing Sun and its effects throughout the Solar System	•Investigation of magnetic storm effects during the peak and the declining phase of the solar cycle
	•Chart our destiny in the Solar System	
Share the excitement and knowledge generated by scientific discovery and improve science education	Education and Public Outreach Objectives •Share the excitement of space science discoveries with the public	•Articles in the popular scientific literature; museum and planetarium exhibits
	•Enhance the quality of science, mathematics, and technology education, particularly at the pre-college level	•Teacher workshops; elementary and secondary curriculum development
	•Help create our 21st century scientific and technical workforce	•Undergraduate and graduate research opportunities
Use robotic science missions as forerunners to human exploration beyond low-Earth orbit	Human Space Flight Operations •Investigate the composition, evolution, and resources of Mars, the Moon and small bodies	
	•Develop the knowledge to improve space weather	•Nearly continuous multi-spectral imaging of geospace; real-time data link for NOAA
Develop new technologies to enable innovative and less expensive research and flight missions	Technology Objectives •Acquire new technical approaches and capabilities •Validate new technologies in space •Apply and transfer technology	•Comprehensive set of new magnetospheric imaging technologies developed, validated in space, and published

Table 2. *IMAGE Contributions to NASA OSS Strategic Plan are shown in red.*

to the development of magnetospheric substorms and geomagnetic storms.

- *IMAGE provides a real-time data link containing its full data set. These data are used operationally by the NOAA Space Weather Forecast Center. These data have also become a public resource for planning auroral viewing.*

- *During the extended mission, when the fuel on Polar has been depleted, IMAGE will become the only spacecraft acquiring nearly continuous global auroral images. In addition, the auroral imaging on IMAGE is immune to "blackouts" caused by solar flare particle events because of its time-delay integration system.*

- *IMAGE provides unique global-scale data on plasma injection and transport, which will provide important tests of current and future theories of solar wind, magnetosphere, ionosphere interactions.*

TECHNICAL SECTION

III. PROGRAM IMPLEMENTATION

A. Existing IMAGE Resources

IMAGE can be considered to be the first "Space Weather Satellite," analogous to the first geosynchronous weather satellite. All IMAGE instruments are providing excellent data, and the mission has exceeded all expectations. Because of its unique imaging data, IMAGE has received extensive coverage in the popular media, and the mission and its E&PO component have received several significant awards from different media groups. IMAGE is providing real-time data to NOAA for space forecasting purposes and will soon be the only spacecraft obtaining nearly continuous auroral imaging data. As a comprehensive global magnetospheric imaging satellite, IMAGE will provide an important baseline of data for the beginning of the Living With a Star program. For these reasons alone it is important to keep IMAGE operating for as long as possible. But in addition, the precession of the IMAGE orbit and the progression of the solar cycle afford the opportunity for an essentially new mission in 2003-2005, one that focuses on the study of recurrent geomagnetic storms from a new imaging perspective.

The spacecraft and instruments are in excellent health, and the Science and Mission Operations Center (SMOC) has been set up for extremely efficient operation, performing spacecraft commanding and data acquisition, all data generation through level-1, and data archiving. The data set is completely open with no proprietary data or periods. The team has implemented a common data format known as the Universal Data Format (UDF) in which all instruments have the same format with ancillary files that contain instrument characteristics and calibration factors. The UDF format allows the user to plot data from all IMAGE instruments, singly or in any combination, with a single set of software.

B. Mission Operations and Data Analysis

1. IMAGE mission operations are automated and efficient. The IMAGE mission is currently operating with a near 100% duty cycle with all instruments working nominally. The SMOC, operated at Goddard Space Flight Center (GSFC), is the main data and command processing system for IMAGE [*Burley et al*., 2000]. The SMOC is operated by 2.5 FTE operations personnel during a normal 40-hour work week. Many of the operations of the SMOC are automated. IMAGE data are recorded on board and dumped twice per day by the Deep Space Network (DSN). The Level-0 data from DSN is transmitted to the SMOC, where it is automatically processed into high-resolution science data (Level 0.5) written in the Universal Data Format (UDF), and browse products (Level 1) written in the Common Data Format (CDF). An automated pager system provides notification to the operators when changes are detected in the configuration of key spacecraft subsystems, instrument parameter limits, or any SMOC computer or hardware configurations. This system provides routine IMAGE data operations in a largely "lights out" manner, making it one of the most cost efficient mission operation systems at GSFC.

2. IMAGE data are nonproprietary. IMAGE is the first space physics mission for which there are no proprietary periods. The SMOC maintains approximately two weeks of all the latest IMAGE data and browse products online from all the instruments. This Web site is open to experimenters as well as the general community at http://150.144.211.77/image/image_main.html. Level-0 IMAGE data is typically used only by the experimenter teams to monitor instrument health and perform calibration. The highest time resolution IMAGE science data are generated by the SMOC into UDF formatted files and are used by the both the IMAGE experimenter teams and any other scientists who want to analyze IMAGE data.

3. IMAGE data are archived at NSSDC and in CDAWeb. Within 48 hours of being received by DSN and processed at the SMOC, all IMAGE data and browse products are transferred to the NSSDC for long-term archiving, and posted immediately on the Web for use by the scientist community and the public. IMAGE browse products are routinely loaded into the CDAWeb system and are completely compatible with, and merged with, the ISTP key parameter data base. The UDF formatted IMAGE science data are loaded into the NSSDC ftp online disk storage area (ftp://nssdcftp.gsfc.nasa.gov) and are immediately available to the community with "around the clock" access. IMAGE data older than two weeks are freely accessible at the NSSDC. Between the SMOC (latest IMAGE data), the NSSDC (older archival data) and CDAWeb (browse products), IMAGE data products are easily available to the entire international science community.

4. IMAGE data analysis software is freely distributed. Much effort has been expended by the IMAGE team to include data analysis software with the IMAGE data. The IMAGE Software Suite (ISS) is accessible on the Web directly at http://image.msfc.nasa.gov/ and has been distributed on CD-ROM at the fall AGU meeting in December 2000. The CD-ROM contains all the software in the form of installation packages. A variety of specialized IMAGE software utilizing JAVA and IDL is available. For UDF, ISS supports Windows and Unix platforms. The Apple/Macintosh UDF analysis software is currently under testing and is expected to be completed by the end of FY01. Once the Apple/Macintosh UDF software becomes operational, the ISS Web site will be updated and a new CD-ROM with the latest software will be advertised through the SPA newsletter and distributed freely upon request.

5. Up-to-date IMAGE information is on the Web. The IMAGE team operates an extensive mission information system on the Web. The prime site for IMAGE is http://pluto.space.swri.edu/IMAGE, which provides extensive IMAGE mission overview information and connections to all other IMAGE Web sites. Each of the instrument teams maintain active Web sites where their latest results can be found. In addition, the IMAGE science center web site is located at http://image.gsfc.nasa.gov/IMAGE/. This site provides extensive information on the team's science publications, abstracts, presentations, IMAGE orbit plots and orbit files, and other mission-specific services.

6. IMAGE data contribute to Space Weather. Although the IMAGE mission primarily transmits data in a store and forward mode with one downlink per orbit, the IMAGE spacecraft has an additional real-time link designed to provide the full data set to NOAA and to any other group capable of receiving the telemetry. NASA has an MOU with NOAA's Space Environment Center (SEC) to provide real-time data necessary to support their operational space weather forecasting needs. NOAA's ground antenna at Fairbanks, Alaska is their main tracking location. In addition to NOAA, several organizations regularly capture IMAGE real-time data. These include: University of California, Berkeley (UCB) and the Communication Research Laboratory (CRL) in Japan. UCB uses its real-time link to post WIC and SI auroral zone images on the FUV Web site, and CRL uses IMAGE data for their space weather forecasting in Japan. In order to fully support these real-time links and provide useful IMAGE data products, a significant portion of the SMOC software has been ported to these locations. The IMAGE SMOC team has been instrumental in providing initial operational support for making the IMAGE real-time data systems successful.

7. IMAGE Team gets the word out. The IMAGE mission was launched on 25 March 2000 and after 62 days (owing to the long period of time required for extending the RPI antennas) became fully operational on 26 May 2000. The IMAGE team has done a creditable job in presenting the mission's results over the first year of operation. **Table 3** shows the number of presentations and papers from the IMAGE team in 2000 and 2001.

It is important to note that a number of the IMAGE presentations and publications have been accomplished by non-IMAGE team members. It is believed that this is directly attributable to the willingness of the team members to reach out and involve the community and to the open data policy and ready access of the IMAGE data. As shown in **Table 3**, the IMAGE data are also being used by young scientists to obtain their advanced degrees. In addition, IMAGE data and team members have been involved in over a half dozen press releases. All IMAGE team meetings (both full team and instrument teams) and workshops are open to the science community. A detailed list of the IMAGE press releases, meetings, publications, and presentations is available at the IMAGE Science Center web site (http://image.gsfc.nasa.gov/).

C. Science Team Structure

The IMAGE Science Team is organized around the six instrument systems with separate components for mission-level operations and science, E&PO, and Theory and Modeling. A significant effort is required at the mission and instrument level for instrument software modifications, instrument monitoring and calibration, and anomaly resolution. Communication among the team is primarily electronic with three to four science team meetings per year for coordination of instrument operations, data analysis, and modeling. Since IMAGE is a P.I.-led mission, most non-government investigators are funded by SwRI subcontracts. Funding for government institutions and their subcontractors is distributed directly to the appropriate government laboratory.

D. Prime Mission

The prime mission started at the end of the initial operating condition (IOC) on 26 May 2000. During the prime mission the spacecraft will be operated for two years with one additional year for data analysis. The apogee remains above the north pole for the two-year prime mission but will be rapidly precessing toward lower latitudes, providing the opportunity for an essentially new mission in 2003-2005.

E. Minimal/Bare Bones Extended Mission

In the proposed budget for the minimal/bare bones extended mission, it is assumed that all science data analysis, theory, and modeling activities are eliminated. It is assumed that the spacecraft will be operated, the instrument performance will be monitored, the data verified and validated, and the data products generated and archived.

F. Requested/Optimal Mission

In the proposed budget for the requested/optimal mission, it is assumed that the spacecraft will be operated and all mission services, science center, and science data analysis activities will be continued as in the prime mission.

With this option, the community will be able to take full advantage of the new opportunities for research that will be available because of the precession of the orbit and the progression into the declining phase of the solar cycle. In the extended mission, full attention will be directed toward these new science goals, but at the same time the full open data set will be maintained for use by the larger community, and E&PO efforts will continue at a high level. One of the more significant aspects of the extended-mission E&PO effort will be the continuation of close coordination with authors of astronomy text books, which historically have included very little, and often outdated, information on the Earth's magnetosphere.

G. IMAGE Education and Public Outreach

1. Phase 2: (2002-2003). The POETRY team will use the products already developed to influence the content of the textbooks that are adopted by county and state curriculum committees. This is the most important phase of the IMAGE/POETRY program.

In 2000, the team was invited by Stephen Shawl to assist with the writing of the undergraduate textbook in astronomy *Discovering Astronomy* (Kendall-Hunt), for which we contributed our CD-ROM and helped to edit the discussion on aurora and the geospace environment. The team has taken

Year	Presentations	Refereed Journals	Conference Proceedings & Other Publications	Popular Magazines	Thesis MS/PhD
Jan-April 2001	52	16	1	1	3
2000	84	20	9	2	0

Table 3. *IMAGE Articles and Presentations*

this textbook collaboration one step further by contacting the authors of extant astronomy textbooks to ask them to update their, usually incorrect, descriptions of the aurora mechanism to conform to establish geophysical principles.

We will continue our collaboration with the NASA/Goddard Office of Education on the design of a new, regional Space Science Curriculum module and will lead a number of workshops in 2002-2003 to design the course content for K-12. This is a rare opportunity for a NASA mission to make a dramatic contribution to what is actually taught in the classroom, and how it is taught.

We will continue our development of planetarium programs begun in Phase 1, and of our museum programs such as "Space Weather" currently at the Houston Museum of Science. The museum software from that exhibit will be integrated into the NASA traveling Space Weather Exhibit, constructed during Phase 1, and now on national tour. We will create another 3-4-minute segment on Sun-Earth connections to be part of the "Sun" planetarium show that we plan to create in the next two years.

2. Phase 3: (2004-2005). Phase 3 will be devoted to the national scope of IMAGE impacting what our children learn about the geospace environment. The K-12 landscape at this scale of impact is the most critical one to affect, and includes 26,000 school districts and textbook adoption committees. Since most teachers teach directly from the textbooks they are provided with, our chief goal is to make a dramatic difference in the accuracy and relevance of the material teachers have when discussing the magnetosphere, the aurora, and the impacts of space weather on human activities and technology. We will work with the NEA/NSTA and with NASA/Code FE to deepen our impact on the national education standards and on the textbook adoption process. We will continue to develop new NASA Educator Guides of "Exemplary" quality to guarantee their wide distribution throughout the NASA system of Broker Institutions and Educator Research Centers. As before, IMAGE products will continue to be heavily leveraged at no cost to IMAGE by being adopted and registered by NASA's Education Office as an official product, and distributed electronically through the NASA CORE program.

The POETRY team will create a major revision to the "Space Weather" software to emphasize the results of IMAGE. We will create another 3-4 minutes of planetarium full-dome content, emphasizing the results of IMAGE, suitable for use in several shows. We will also create a scenario for a "Challenger Center" program which involves a space storm, using spacecraft such as STEREO to observe the CME, and IMAGE to observe its effects on Earth.

BUDGET

The budget spread sheet is shown in the requested format in Figure 22. After FY01 an inflation factor of 3% per year is used. The E&PO activity is accomplished within the science team, so its budget is included in Item 4 (Science Data Analysis). Two sets of figures are necessary to represent the in-guide and minimal budgets for FY02 and FY03 because the in-guide plan calls for turning off the spacecraft on 26 May 26 2002 and ending data analysis activities on 26 May 26 2003. For these two years, the in-guide columns and the minimal columns are separate and all inclusive, so either one but not both should be chosen. The in-guide science manpower for FY 03 is anomalously low but is offset by higher than normal figures in FY02. This results from the existing funding profile, which does not accurately represent the division of effort between FY02 and FY03. The increased level of effort for science data analysis for the requested/optimal scenario results from the very tight budget of the prime mission. Effective use of the IMAGE data requires the listed increase in manpower.

References

Brandt, P. C., et al., Global ENA observations of the ring current: Pitch angle distributions and interactions with the plasmasphere during storm, *J. Geophys. Res.,* submitted, 2001a.

Brandt, P. C., et al., Global ENA observations of the ring current: Rapid dayside ion drop out, *J. Geophys. Res.*, submitted, 2001b.

Brittnacher, M., et al., Polar cap area and boundary motion during substorms, *J. Geophys. Res., 104,* 12,251, 1999.

Burch, J. L., The fury of space storms, *Sci. Am.*, 86-94, Apr. 2001a.

Burch, J. L., IMAGE: Image for Magnetopause-to-Aurora Global Exploration, Goddard Space Flight Center Scientific Colloquium, February, 2001b.

Burch, J. L., et al., Views of Earth's magnetosphere with the IMAGE satellite, *Science, 291,* 619-624, 2001a.

Burch, J. L., et al., Global dynamics of the plasmasphere and ring current during magnetic storms, *Geophys. Res. Lett., 28,* 1159-1162, 2001b.

Burley R. J., et al., The IMAGE Science and Mission Operations Center, *Space Sci. Rev., 91,* 483-496, 2000.

Bzowski, M., et al., Interplanetary neutral paticle fluxes influencing the Earth's atmosphere and the terrestrial environment, *Icarus, 124,* 209-219, 1996.

Collier, M.R., et al., Observations of neutral atoms from the solar wind, *J. Geophys. Res.,* in press, 2001.

Cornwall, J. M., et al., Turbulent loss of ring current ions, *J. Geophys. Res., 75,* 4699-4709, 1970.

Ebihara and Ejiri, Quantitative ring current model: Overview and comparison with observations, *Adv. in Polar Upper Atm. Res., 13,* 1-36, 1999.

Frey, H. U., et al., The electron and proton aurora as seen by IMAGE-FUV and FAST, *Geophys. Res. Lett., 28,* 1135-1138, 2001.

Fuselier, S. A., et al., Multi-instrument observations from IMAGE, *EOS Trans. AGU, 81,* Fall Meet. Suppl., Abstract SM71B-03, 2000a.

Fuselier, S. A., et al., Stability of the high-latitude reconnection site for steady northward IMF, *Geophys. Res. Lett., 27,* 473-476, 2000b.

Fuselier, S. A., et al., Ion outflow observed by IMAGE: Implications for source regions and heating mechanisms, *Geophys. Res. Lett., 28,* 1163-1166, 2001.

Goldstein, J., et al., MSM simulation of the plasmaspheric shoulder, and comparison to data from IMAGE EUV, submitted to Spring AGU Meeting, 2001.

Grebowsky, J. M., Model study of plasmapause motion, *J. Geophys. Res., 75,* 4329, 1970.

Green, J. L., Overview of the observations from the Radio Plasma Imager on IMAGE, *Eos Trans. AGU, 81,* Fall Meet. Suppl., Abstract SM71B-02, 2000.

Henize, V., et al., An empirical model of the polar cap density profile from the IMAGE radio plasma imager, to be submitted to *J. Geophys. Res.,* 2001.

Lin, J., et al., A semikinetic model of early stage plasmasphere refilling, 2, effects of wave-particle interactions, *J. Geophys. Res., 97,* 1121-1134, 1992.

Lockwood, M., and M. F. Smith, The variation of reconnection rate at the dayside magnetopause and cusp ion precipitation, *J. Geophys. Res., 97,* 14,841-14,847, 1992.

Mende, S. B., et al., Global observations of proton and electron auroras in a substorm, *Geophys. Res. Lett., 28,* 1139-1142, 2001a.

Mende, S. B., et al., Electron and proton auroral dynamics during substorm recovery phase, submitted to *Geophys. Res. Lett.,* 2001b.

Milan, S. E., et al., Dayside convection and auroral morphology during an interval of northward interplanetary magnetic field, *Ann. Geophysicae, 18,* 436-444, 2000.

Moore, T. E., et al., Microscale effects from global hot plasma imagery, in *Cross-Scale Coupling in Space Plasmas,* eds. J. L. Horwitz, N. Singh, and J. L. Burch, 37-46, Geophysical Monograph No. 93, American Geophysical Union, Washington, D.C., 1995.

Moore, T. E., et al., Low energy neutral atoms in the magnetosphere, *Geophys. Res. Lett., 28,* 1143-1146, 2001.

Newell, P. T., et al., Some low-altitude cusp dependencies on the interplanetary magnetic field, *J. Geophys. Res., 94,* 8921, 1989.

Odenwald, S., *The 23rd Cycle,* Columbia University Press, New York, NY, 2001.

Perez, J. D., et al., Deconvolution of energetic neutral atom images of the Earth's magnetosphere, *Space Science Rev., 91,* 421, 2000.

Perez, J. D., et al., Initial ion equatorial pitch angle distributions from medium and high energy neutral atom imagers obtained by IMAGE, *Geophys. Res. Lett., 28,* 1155-1158, 2001.

Persoon, A. M., D. A. Gurnett, S. D. Shawhan, Polar cap electron densities from DE-1 plasma wave observations, *J. Geophys. Res., 88,* 10123, 1983.

Reinisch, B. W., et al., First results from the Radio Plasma Imager on IMAGE, *Geophys. Res. Lett., 28,* 1167-1170, 2001.

Sandel, B. R., et al., Initial results from the IMAGE extreme ultraviolet imager, *Geophys. Res. Lett., 28,* 1439, 2001.

Singh, N. and J. L. Horwitz, Plasmasphere refilling: Recent observations and modeling, *J. Geophys. Res., 97,* 1049-1080, 1992.

Taylor, W. W. L. and L. R. Lyons, Simultaneous equatorial observations of 1- to 30-Hz waves and pitch angle distributions of ring current ions, *J. Geophys. Res., 81,* 6177-6183, 1976.

Tsurutani, B. T., et al., Interplanetary origin of geomagnetic activity in the declining phase of the solar cycle, *J. Geophys. Res., 100,* 21,717, 1995.

Williams, D. J. and L. R. Lyons, The proton ring current and its interactions with the plasmapause: Storm recovery phase, *J. Geophys. Res., 79,* 4195-4207, 1974.

Wilson, G. R., et al., A semi-kinetic model for early stage plasmasphere refillig, 1, Effects of Coulomb collisions, *J. Geophys. Res., 97,* 1109-1120, 1992.