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

Senior Review 2003

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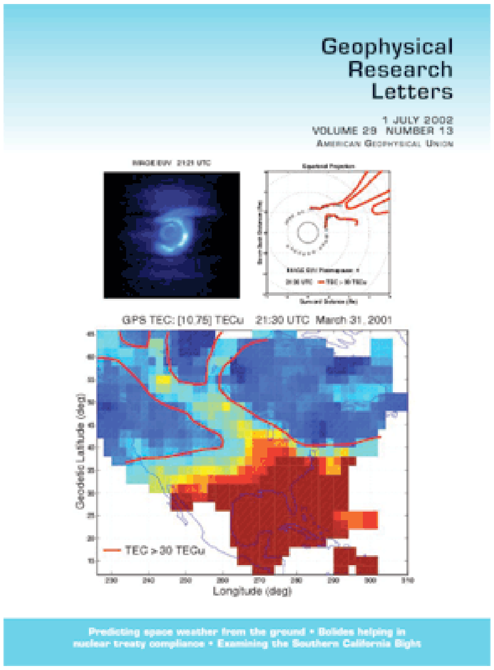

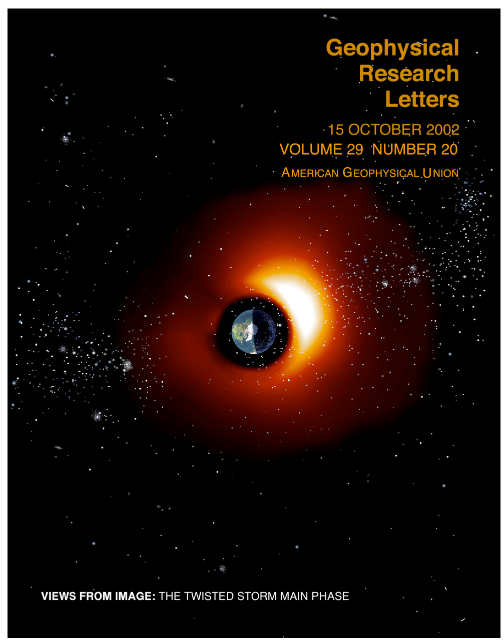

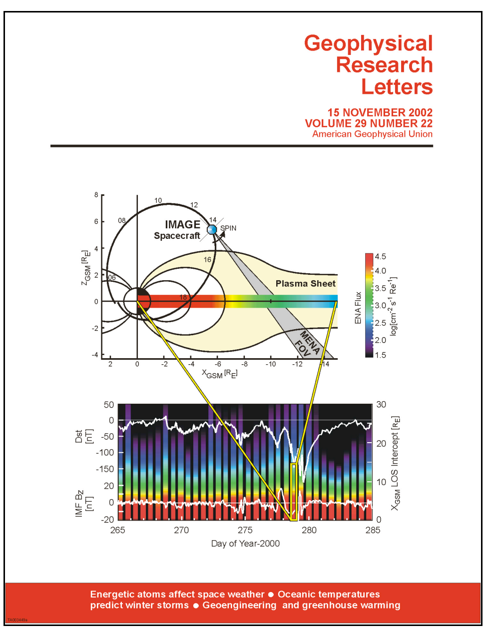

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EXECUTIVE SUMMARY

The Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) is the first satellite mission dedicated to imaging Earth's magnetosphere. Using advanced energetic neutral atom and ultraviolet imaging techniques along with omnidirectional radio sounding, IMAGE has provided the first global views of the structure and dynamics of plasmas in the inner magnetosphere and has achieved the full set of scientific objectives of its prime mission. Each of the six IMAGE instruments has contributed significantly to IMAGE's scientific success, 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. Since its inception, the IMAGE data system has been completely open to the community. All data to their full resolution and software needed for data display and analysis are freely available to the community. The IMAGE team has never claimed any proprietary rights or placed any limitations on use of the data. IMAGE has also contributed data 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.

Extended Mission. IMAGE is now in its extended mission phase, during which the migration of the line of apsides toward lower latitudes (at a rate of 50 deg/yr) has resulted in a change in imaging perspective that supports a range of innovative studies that could not be performed from the high- and mid-latitude apogee of the prime mission. As apogee continues to evolve to higher latitudes in the southern hemisphere, investigations of hemispheric differences (e.g., in auroral phenomena) will be possible. In addition, because the extended mission is taking place during the declining phase of the solar cycle, IMAGE can observe the global effects of recurrent storms and compare them with those associated with the CME-driven storms observed during the prime mission. IMAGE will also continue to provide real-time auroral imaging data to NOAA and other interested institutions.

Status of the IMAGE Mission. The IMAGE spacecraft and all instruments are operating nominally, and there is every expectation that they will continue to do so for many more years. The precession of apogee to the southern hemisphere will not affect operations in the baseline store-and-forward data transmission mode. However, for reception of real-time data, which are transmitted continuously for space forecasting purposes as well as for backing up occasional data loss in the store-and-forward mode, a southern hemisphere receiving station will have to be used.

IMAGE Data System. The IMAGE data can be accessed from centralized web sites/servers at GSFC (both at the IMAGE Science and Mission Operations Center (SMOC) and the National Space Science Data Center (NSSDC)), as well as through web sites maintained by the individual instrument groups. Level-1 data are available from the SMOC within 24 hours of their receipt from the Deep Space Network (DSN). Level-1 data include CDF files and GIF images from all instruments at their full time resolution but with a limited set of wavelengths, energies, and species. The full data sets are available within three days in the Universal Data Format (UDF) [*Gurgiolo*, 2000]. The software needed to acquire, plot, and analyze UDF data is available for free download from several sites, and for virtually all conceivable platforms (UNIX, Windows, Mac OS-X).

Education and Public Outreach. The IMAGE EPO program, called POETRY (Public Outreach Education, Teaching and Reaching Youth) was implemented several years before launch and is well integrated into the Sun-Earth Connections Education Forum. It has received national recognition and awards for books, curricula (primary through secondary), teacher training events, interactive web site, museum kiosks, educational video, and planetarium exhibits. During the extended mission, the IMAGE POETRY program will continue to produce high-quality and innovative education products that explain space physics concepts to teachers and students in the K-12 community and the public.

Award Winning Mission. Since the last Senior Review, IMAGE was selected by NASA Headquarters as the "Best OSS Mission" and Jim Burch received the award in September 2002 on behalf of IMAGE at the Enterprise Showcase of Best Projects at the Project Management Shared Experience Program 2002 in Reston, VA. In addition, William Gibson (SwRI) was awarded the NASA Public Service Medal for his successful management of the IMAGE mission from inception through launch. This medal is the highest level of award NASA gives to a non-NASA employee.

IMAGE Publications and Presentations. Since January 2000, 138 papers using IMAGE data or describing IMAGE instrumentation have been published or accepted for publication or are in review. Of these, a little over one fourth have first authors who are not members of the original IMAGE team. Of these, Cluster investigators account for nine papers and ground-based investigations account for another eight papers. Reflecting the importance that the space physics community attaches to the IMAGE observations, between July 1 and December 15, 2002, IMAGE results were featured four times on the cover of *Geophysical Research Letters*. In addition, IMAGE results have been reported in over 400 presentations at scientific conferences and in other venues. Five Ph.D. theses using IMAGE data have been completed, and six more are in progress. **Table 1** summarizes the IMAGE publication record by instrument. Many of the papers use data from more than one IMAGE instrument. In those cases, either the primary data source or the affiliation of the first author was used to classify the paper. Papers listed under "all" involve the entire IMAGE payload. An on-line bibliography of IMAGE publications can be found at the URLs: http://image.gsfc.nasa.gov/publication/ and http://pluto.space.swri.edu/IMAGE/.

The following proposal summarizes IMAGE's key accomplishments and presents the new mission (Section I); reviews the technical status of the instruments, spacecraft, and ground segment, discusses IMAGE data availability and dissemination, and presents the budget for the new mission (Section II); and presents the accomplishments and future plans of the IMAGE EPO program (Section III).

I. SCIENCE

A. 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

Table 1. *IMAGE papers and presentations.*

	FUV	EUV	HENA	MENA	LENA	RPI	All	Total
Papers (totals)	44	14	15	12	17	25	11	138
Published	28	8	9	7	11	14	10	87
In Press	13	2	3	4	4	3	1	30
In Review	3	4	3	1	2	8		21
Presentations	120+	50+	~29	25	35+	141		400+
Theses (total)	3	1	2	1	1	3		11
Completed	1	1		1		2		5
In Progress	2		2		1	1		6

Table 2. *IMAGE science instruments.*

Imager	Lead Investigator	Objectives	Measurements
LENA (Low-Energy Neutral Atom)	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° x 360°, angular resolution of 8°, and energy resolution of 80%.
MENA (Medium-Energy Neutral Atom)	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° x 120°, angular resolution of 8°, and energy resolution of 80%.
HENA (High-Energy Neutral Atom)	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° x 107°, angular resolution of 8°, and energy resolution of 80%.
EUV (Extreme Ultraviolet)	Bill R. Sandel, University of Arizona	Image plasmasphere	Extreme ultraviolet irradiance at 30.4 nm with field of view of 90° x 90° and angular resolution of 0.6°.
FUV (Far Ultraviolet)	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 (Radio Plasma Imager)	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.

storms and substorms? **Table 2** lists the six instruments that were designed to address these questions. It also illustrates their measurement capabilities. After three years of operation, each instrument continues to perform well and to contribute to the science objectives in a significant way.

IMAGE is the first satellite mission dedicated to imaging the Earth's magnetosphere; soon after launch, it began providing global images of the important plasma populations in the inner magnetosphere. These images led immediately to numerous new discoveries and confirmation of several existing theories regarding magnetospheric plasma dynamics. Some of these ***early science results*** included:

- proof of the existence of the plasma tails predicted during magnetic storms by global magnetospheric convection models [*Burch et al*., 2001a,b];
- discovery of several new and unpredicted features of the plasmasphere including "shoulders," "fingers," corotating "voids," and isolated flux tubes [*Sandel et al*., 2001];
- demonstration that south-north transitions in the interplanetary magnetic field (IMF) produce the observed plasmasphere shoulders [*Goldstein et al*., 2002];
- determination of the energy-dependent injection and drift of energetic ions during magnetospheric substorms [*Burch et al*., 2001a; *Pollock et al., 2001; Mitchell et al.,* 2001];
- the first global images of the proton aurora, establishing its source with correlative measurements of proton precipitation on FAST, and determining the dynamical relationship between electron and proton auroras during substorms [*Frey et al*., 2001; *Mende et al*., 2001];
- discovery of neutral-atom components of the solar wind, caused by charge exchange with interstellar neutrals and exospheric atoms in the magnetosheath [*Moore et al*., 2001; *Collier et al*., 2001];
- the first measurements of interstellar neutral

atoms from the inner solar system [*Collier et al.*, 2003]; and

- the first remote measurements of plasmaspheric densities using radio sounding [*Reinisch et al.*, 2001].

A.1 Recent Science Results

In addition to the dramatic new images that the early mission obtained, IMAGE results have produced a more general level of understanding in several important scientific areas that would simply never have been obtained without global imaging. This new understanding results from a combination of completely unexpected observations and verification of long-standing theoretical predictions, which in at least one case did not conform to current understanding and so had been suppressed for years. Some examples of these new paradigms are as follows:

- *Antiparallel reconnection occurs at the high-latitude dayside magnetopause for northward IMF, while component reconnection occurs at the subsolar magnetopause for southward IMF*. The results of *Fuselier et al.*, [2002a; 2003] verified the high-latitude dayside magnetopause reconnection predictions of *Crooker* [1999] with images of the proton aurora from IMAGE-FUV for northward IMF. The images taken during southward IMF indicated reconnection occurring over a broad region of the dayside, confirming component reconnection as described by *Gosling et al.* [1990].
- *Reconnection is a continuous process*. The observations of *Frey et al*. [2002] and *Fuselier et al*. [2002a; 2003] showed that reconnection is continuous, occurring without pause for many hours. Furthermore, reconnection does not stop and start as the IMF changes, it simply shifts location.
- *Detached subauroral proton arcs occur in the afternoon sector during magnetic storms when either IMF-B_Y or IMF-B_Z changes from negative to positive*. The predictions of *Burch et al*. [1985] and *Cowley et al.* [1991] that the afternoon-sector auroral oval moves poleward for positive IMF-B_Y were verified with proton aurora images [*Burch et al.*, 2002]. This poleward motion of the oval, which occurs for all local times when IMF-B_Z turns northward, causes the separation of the subauroral proton arc from the main proton oval.
- *The peak of the ring-current proton distribution during the main phase of magnetic storms is in the early morning sector and moves more towards dawn as IMF-B_Y becomes more positive*. As shown in **Figure 1**, global ring-current images from IMAGE-HENA reveal that changes in IMF-B_Y cause skewing of the inner-magnetosphere convection electric field, which distorts the drift paths of ring current ions, causing them to veer more into the morning sector before beginning to drift westward [*Brandt et al*., 2002]. This result was initially met with skepticism because the main-phase decrease of the surface magnetic field (the so-called low-latitude asymmetric disturbance field) was generally attributed to a dusk-centered partial ring current. Computer models and analytic theory showed over 20 years ago that the low-latitude asymmetric disturbance field was instead caused by net field-aligned currents flowing into the ionosphere at noon and out at midnight [*Harel et al*., 1981; *Crooker and Siscoe,* 1981; *Chen et al*., 1982]; but this theoretical result was not widely accepted until the IMAGE observations were reported.
- *Kilometric continuum radiation is produced at the inner edge of plasmaspheric notches or bite-outs and is beamed outward into the dayside magnetosphere*. In one event, the structure of plasmaspheric notches was first imaged by IMAGE-EUV and later penetrated by the IMAGE spacecraft from which IMAGE-RPI was able both to detect the kilometric radiation and identify the boundaries of the notch [*Green et al*., 2002]. Kilometric contin-

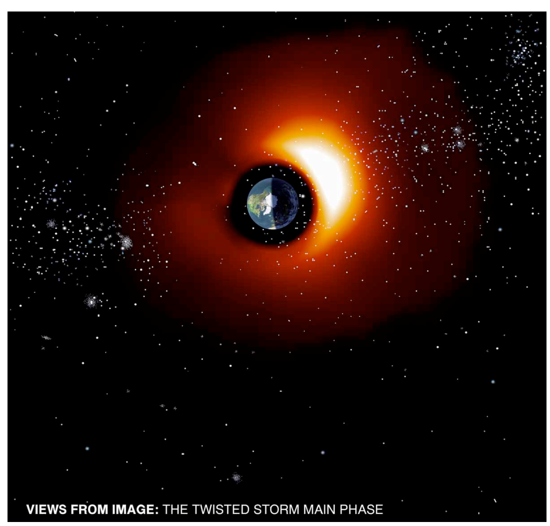

Figure 1. *HENA image of ring current injection in the post-midnight region at 1700 UT on October 4, 2000. The color intensity is proportional to the proton pressure at energies <60 keV [Brandt et al., 2002a].*

uum radiation has been routinely detected by Geotail [*Hashimoto et al.,* 1999] and was thought to come from the plasmasphere, but the connection to plasmaspheric notches and their role in beaming the radiation was not known.

• *Plasmaspheric tails map along magnetic field lines to the ionosphere where they are associated with plumes of high total electron content (TEC), which disrupt GPS signals [**Figure 2**].* The results of *Foster et al.* [2002] show that the plasmaspheric tails represent one of the most intense space-weather effects yet discovered, which is surprising because they occur at latitudes below the auroral zone. The GPS outages associated with the plasmaspheric tails and the associated TEC plumes in the ionosphere can cause serious problems for civilian and military users of GPS.

• *The ionosphere responds rapidly and dramatically to changes in the solar wind.* Images of the ion outflow from the ionosphere from IMAGE/LENA demonstrated that rapid changes in the solar wind dynamic pressure result in episodic bursts of ion outflow [*Fuselier et al.,* 2002b]. By combining these images with auroral images from FUV, it was also shown that the bursts are confined to regions of the auroral oval where there are intense auroral emissions. This result was featured in the first-ever Space Science Update on magnetospheric processes, which was held at NASA Headquarters in May 2002.

• *Ionospheric oxygen ions are injected into the ring current during magnetospheric substorms that occur during the recovery phase of magnetic storms.* IMAGE-HENA forms separate ENA images for hydrogen and oxygen. As shown by *Mitchell et al.* [2003], the hydrogen component of the ring current builds up and decays gradually in concert with the Dst index. In contrast, the oxygen component rises and falls impulsively, following more closely the AE index. **Figure 3** shows the unique oxygen ENA enhancements at the time of auroral substorms as seen in WIC images. This result formed the basis for the Space Science Update (SSU) that was held at NASA Headquarters in May 2002.

• *The occurrence of magnetic storms is preconditioned by the existence of (1) a southward IMF component with significant magnitude and duration, and (2) the existence of a significantly dense reservoir of plasma in the magnetotail. McComas et al.* [2002] used the IMAGE-MENA instrument to

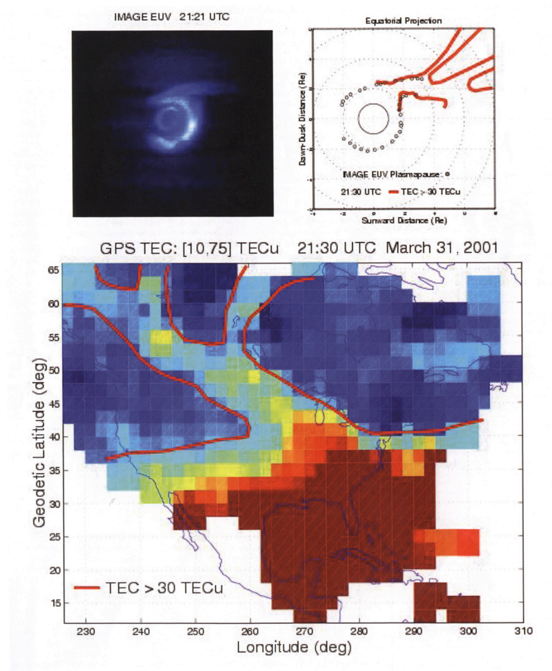

Figure 2. *(Top left) Space-based IMAGE-EUV observations of the plasmasphere reveal a sunward-directed plasma tail. (Top right) Circles denote the plasmapause position scaled from the EUV image. Superimposed in red is the equatorial-plane projection of the >30 TECu (total electron content units) boundary determined from ground-based GPS observations. (Bottom) GPS navigation signals monitored at >120 sites are analyzed to provide a snapshot of ionospheric TEC over North America during the major geomagnetic storm of 31 March 2001. A large-scale plume of storm-enhanced density (SED) spans the continent from a source region in the eastern U.S. The bold contour at TEC>30 units outlines the low-altitude footprint of the TEC plume, which maps directly into the plasmaspheric tail observed by IMAGE-EUV [Foster et al., 2002].*

image the plasma sheet out to distances of 15 R_E and found that, for the 20-day interval examined, the existence of more intense ENA emissions from the plasma sheet was required in order for a significant southward-IMF event to result in a strong magnetic storm (**Figure 4**). Following a strong storm, the plasma sheet becomes depleted and apparently needs to be replenished to a sufficient level before another strong storm can occur. McComas et al. suggested that ENA monitoring of the plasma sheet content, along with IMF measurements, could provide a good predictor of strong magnetospheric activity.

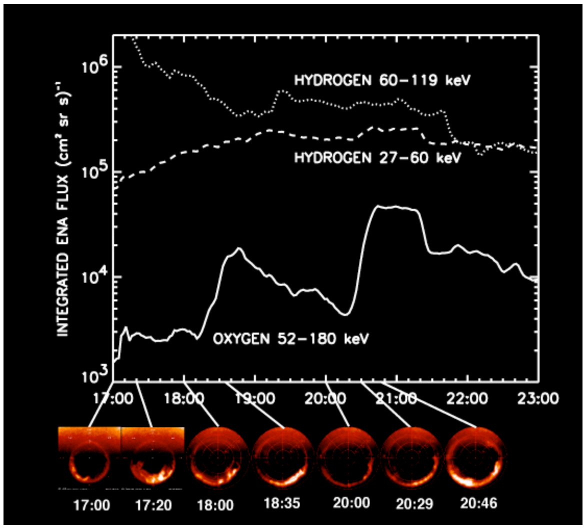

Figure 3. *Plot showing large increases in integrated oxygen ENA flux in association with substorms seen in the WIC images. Hydrogen ENA fluxes do not show these increases [Mitchell et al., 2003].*

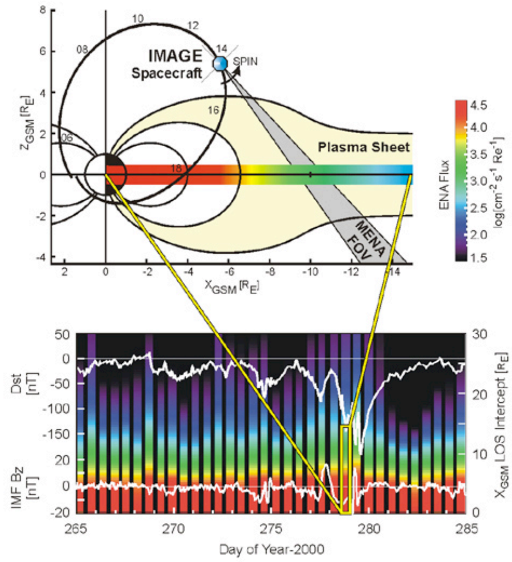

Figure 4. *(Top) Image spacecraft and orbit, showing how MENA scans the plasma sheet as the spacecraft spins. The color scale indicates the plasma sheet density as a function of distance down the tail. (Bottom) White traces show Dst and IMF B_Z. Color bars show plasma-sheet density as a function of down-tail distance for time intervals between day 265 and day 285 of year 2000 [McComas et al., 2002].*

A.2 Latest Science Results

Numerous other ground-breaking results are being obtained with research on IMAGE data, some of which have not yet been published. The list of these latest notable findings includes:

- The angular velocity of cold plasma of the plasmasphere usually lags corotation by 10-15%, even as near Earth as L=2 [*Sandel et al.*, 2003]. This surprising result has not yet been explained.
- A relationship between events of rapid plasmasphere erosion and southward turnings of the IMF has been demonstrated using EUV images [*Goldstein et al.*, 2003a].
- Global plasma pressure distributions obtained from individual HENA images have been used to derive global 3D current systems (perpendicular to **B** and field-aligned) [*Roelof et al.*, 2003a; *Brandt et al.*, 2003].
- IMAGE-FUV SI13 performed the first space-based imaging of drifting low-latitude plasma depletions associated with the spread-F phenomenon and developed a technique for measuring their drift speeds [*Immel et al.*, 2003].
- RPI observations of guided echoes provided a critical test of the field-line inter-hemispheric plasma (FLIP) model of plasmaspheric refilling. The results of *Tu et al*. [2003] show an increase of density away from the equator compared to the FLIP model and suggest a source of direct plasma heating during the refilling process.

B. Extended Mission to 2007

The progression through the solar cycle and the precession of the IMAGE orbit (**Figure 5**) will provide the opportunity for an essentially new mission for IMAGE during the years 2004 through 2007. The focus of the new mission will be on the recurrent magnetic storms associated with high-speed solar wind streams and corotating interaction regions, low-latitude observations of equatorial airglow, conjugate observations of the southern hemisphere aurora, and the use of southern-hemisphere imaging to test the predictions of IMF B_Y-dependent global reconnection models.

IMAGE was launched into a polar orbit (90^o inclination) with 8.2 R_E geocentric apogee and 1000 km perigee altitude on March 25, 2000. Orbit precession for IMAGE moved the apogee over the northern pole during its prime mission phase (2000-2002). Beyond the prime mission, the progression of the IMAGE orbit is shown in **Figure 5**. The orbit precession causes the imaging perspective to evolve from mid latitudes through low latitudes and into the southern polar cap. The low-latitude apogee

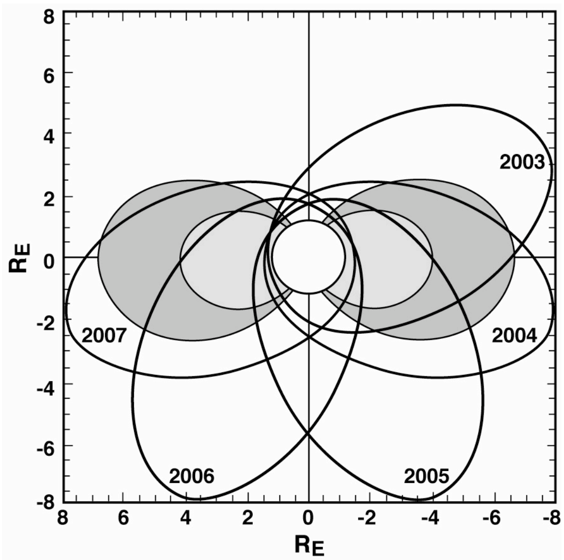

Figure 5. *Orbits for March 25 of each year during the IMAGE extended mission. Orbits are plotted in the orbit plane, in which right ascension = 12° (left half plane) and 192° (right half plane). The local-time precession is not shown since the 90°-inclination orbit is fixed in inertial space.*

phase, which IMAGE is now entering, allows: (1) imaging of the field-aligned distribution of the ENA and EUV emissions, (2) imaging of the aurora (FUV) and the ionospheric outflow (LENA) with higher spatial resolution in both hemispheres in the ascending and descending parts of the orbit, (3) conjugate imaging of the aurora with FUV, and (4) the best opportunity for RPI to sound the magnetopause and track its motion. The southern-hemisphere apogee phase (2005-2006) will allow important comparisons to be made with prime mission imaging of the northern-hemisphere proton aurora to test various predictions of reconnection models. Both phases will provide the opportunity for continuous global imaging through the declining phase of the solar cycle.

During the extended mission to 2007, IMAGE will be the only spacecraft obtaining nearly continuous global auroral images (after the on-board fuel is depleted on Polar), will provide stereo neutral-atom imaging as soon as the first TWINS spacecraft becomes operational in 2004, 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 provide important global context for TIMED, Polar, and Cluster and will be an important early complement to the Living with a Star program.

From 2003 through 2007, magnetic activity will in general wane, but the mostly CME-driven storms of solar maximum will be replaced by the recurrent storms that typically occur during the declining phase of the solar cycle in association with coronal holes [*Tsurutani et al*., 1995]. IMAGE has already demonstrated that the hydrogen and oxygen constituents of the ring current behave differently for CME-driven storms. Critical in this behavior is the time history of the ring current oxygen [*Mitchell et al*., 2003]. However, it is possible that the H^+ and O^+ response to smaller, more frequent storms could be different from the response to large, infrequent storms, between which the magnetosphere has time to recover.

Another important solar-cycle-driven aspect of the magnetosphere is ionospheric outflow [*Fuselier at al.,* 2002b]; but 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. Timing of the oxygen escape [*Fuselier et al*., 2001] as a function of the solar cycle will distinguish between these energization mechanisms.

As the orbit apogee precesses across the equator and over the southern pole by 2006, the changing views will allow global observations of equatorial airglow and conjugate observations of the Earth's southern hemisphere aurora. The global observations of equatorial airglow provide important precursor observations of the mid-latitude ionosphere that will be studied extensively by the Living with a Star Geospace missions. These observations also complement the TIMED observations of airglow.

Observations of the Earth's southern hemisphere aurora will provide a conclusive test of competing models of magnetic reconnection and will complete the picture of field line mapping between the ionosphere and the magnetotail during substorms. As predicted by magnetic reconnection, aurora in the southern hemisphere cusp should behave in a mirror-image fashion as compared to the northern hemisphere [*Reiff and Burch*, 1985]. Both should have the same B_Z dependence, but their B_Y dependence should show opposite responses. For example, for positive B_Z, positive B_Y components should produce a cusp spot on the afternoon side of noon in the northern hemisphere and on the morning side of noon in the southern hemisphere.

Imaging the nightside aurora from the southern hemisphere will also yield new insight into magnetic field mapping during the reconfigurations of the magnetotail that occur during substorms. And indeed, early results from IMAGE/Polar conjugate aurora studies show a skewing of the nightside aurora with B_Y that is similar to that for the cusp aurora [*Østgaard et al.*, 2003]. Furthermore, ground-based observations of the northern hemisphere aurora are much more numerous than those in the southern hemisphere. Thus, the near-continuous global imaging of the southern aurora with IMAGE, combined with detailed ground-based observations of the northern hemisphere aurora, will provide a unique opportunity to perform conjugate auroral studies.

B.1 High-speed Stream/CIR Effects

The solar wind has several distinct characteristics that influence the magnetosphere and ionosphere in diverse ways. The presence of southward interplanetary B_Z is well-known to strongly influence the coupling of solar wind energy into the magnetosphere, but this occurs mainly on short time scales, with B_Z averaging near zero over the longer term. During the period of high solar activity since IMAGE was launched, coronal mass ejections, which enhance primarily the density of the solar wind, have been the main source of geoeffective space weather events with time scales of days. During the declining phase of solar activity now beginning, we can anticipate that well-defined coronal holes will create regions of high-velocity solar-wind streams with a solar-rotation recurrence pattern. These high-speed streams and resultant corotating interaction regions produce the highest levels of geomagnetic activity over time scales of months to years [*Holzer and Slavin*, 1981]. It is very important to continue IMAGE remote sensing of the magnetosphere during this period when the character and mean level of geomagnetic activity will make a fundamental transition to velocity-driven, as contrasted with density-driven, space weather.

Along these lines, *Scime et al.* [2002] demonstrated the ability to derive temperature maps of the near-Earth plasma sheet using MENA images sorted by energy. That group is now expanding their work, applying statistical methods to combine large numbers of ENA images collected at various states of magnetospheric activity, as represented by the Dst index, to derive a set of magnetospheric images that are typical of the various activity levels. Applying this technique to both the early mission solar max interval and the solar minimum period during the extended mission will provide a synoptic view of the response of the magnetosphere to the two solar activity extremes.

B.2 Conjugate Aurora: The Cusp

As the IMAGE orbit apogee precesses below the equator, imaging of the southern hemisphere aurora will commence. IMAGE has already demonstrated that the cusp aurora (in the northern hemisphere) response to the IMF is consistent with the interpretation that these aurora are created by precipitation of protons from magnetic reconnection at the magnetopause. If true, then there are predictions that will ultimately confirm this interpretation. **Figure 6** shows predictions for the cusp in the northern and southern hemispheres for 21 June (summer solstice) when the IMF is southward and has a positive B_Y component. The cusp footprint in the two hemispheres is different, mainly in local time extent. Furthermore, IMAGE observations show that the split neutral line produced by anti-parallel reconnection (top panel) results in significant differences in the energy of the precipitating protons and therefore a difference in the cusp aurora [*Petrinec and Fuselier*, 2003]. In particular, neutral lines that are above (below) the equator produce higher energy protons in the northern (southern) high-latitude ionosphere. For the conditions in **Figure 6** (B_Y>0, summer solstice), it is predicted that the proton aurora will be more intense on the dusk side in the northern hemisphere but on the dawn side in the southern hemisphere. Since there is a part of the neutral line that extends below the equator on the dusk side (top panel in **Figure 6**), there will also be some intense southern-hemisphere cusp aurora on both the dawn and dusk sides with a “gap” near noon. Similar predictions have been developed for other seasons and for both hemispheres. These seasonal predictions will be used in the extended mission to determine if the split neutral line correctly predicts the IMAGE-FUV observations. Correct prediction of the proton aurora images will be strong support for anti-parallel reconnection at the Earth’s magnetopause.

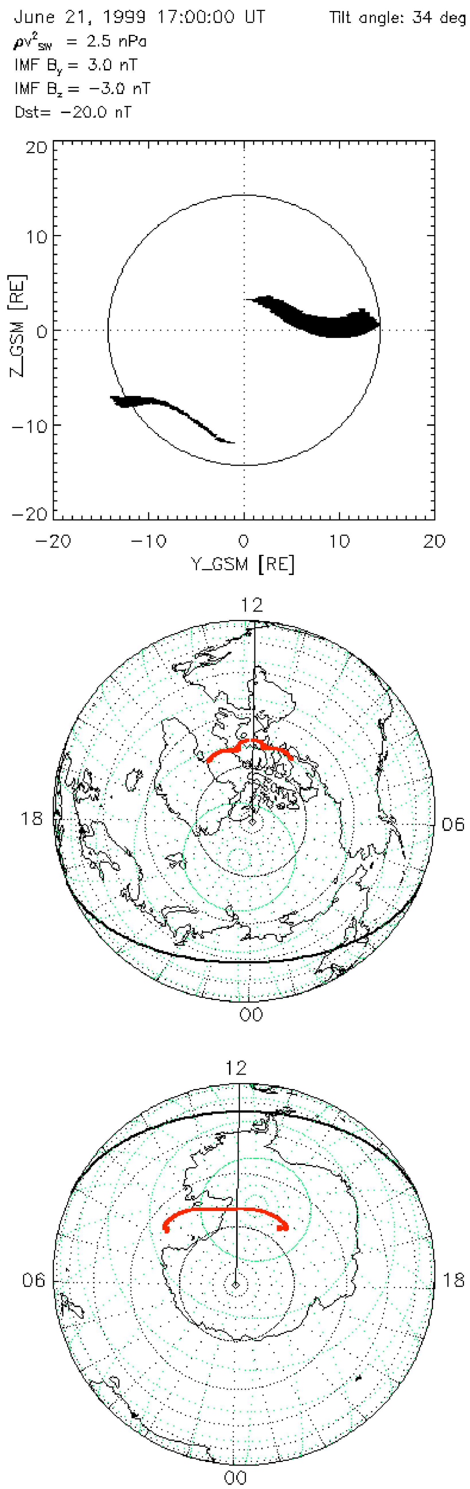

Figure 6. *(Top) locus of antiparallel neutral lines on the magnetopause for IMF B_y = 3nT and IMF B_z = -3nT. (Bottom) Predicted cusp aurora in the northern and southern hemispheres for southward IMF (for both positive and negative values of B_y). The red traces show the magnetic mapping of the antiparallel merging lines to the ionosphere. [Petrinec and Fuselier, 2003].*

B.3 Low-Latitude Dayside Reconnection: Polar-IMAGE Correlations

One of the significant outstanding questions about reconnection is where it occurs on the dayside magnetopause. Two competing models exist. In the first model, reconnection occurs along line(s) (i.e., neutral lines) where the magnetosheath and magnetospheric magnetic fields are antiparallel. **Figure 7** shows that, for B_Z<0 and B_Y<0, the antiparallel neutral lines extend from the northern and southern hemisphere cusps toward the equatorial plane. In the second model, reconnection occurs along a line (tilted neutral line) that is hinged at the subsolar point and is tilted depending on the sign of the IMF B_y component. These two models are called the antiparallel and component reconnection models, respectively.

The IMAGE extended mission provides a unique opportunity to combine Polar and IMAGE observations to distinguish between these two competing models. **Figure 7** shows how combined observations by Polar at the magnetopause and images of the proton aurora from IMAGE will test these models. As the Polar apogee approaches the equatorial plane, it will cross the magnetopause at low latitudes. For appropriate IMF orientations such as in **Figure 7**, the flow direction of the reconnected flows in the low-latitude boundary layer will determine whether the neutral line is equatorward of the spacecraft (component reconnection with northward directed flows) or poleward of the spacecraft (anti-parallel reconnection with southward-directed flows). Simultaneous images of the proton aurora will confirm this identification by determining whether the aurora terminates at noon (anti-parallel reconnection) or extends smoothly across noon (component reconnection). Similar predictions exist for imaging in the southern hemisphere and for IMF B_Y>0.

B.4 Ionospheric Studies

As the orbit apogee precesses across the equator and over the southern pole by 2006, the changing views will allow global observations of equatorial airglow and the mid- and low-latitude ionosphere. These global observations provide important precursor observations of the mid-latitude ionosphere that will be studied extensively by the Living with a Star Geospace missions. These ob-

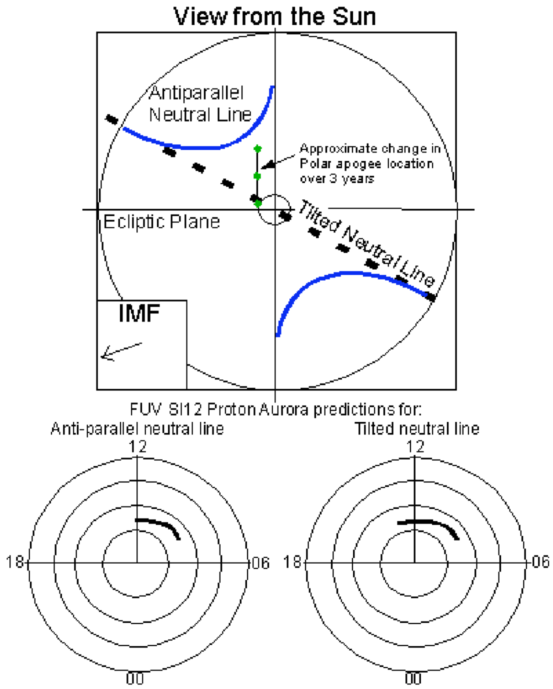

Figure 7. *For the conditions $B_Z<0$ and $B_Y<0$, anti-parallel neutral lines are shown in blue, and the tilted neutral line predicted by component reconnection is shown dashed. Cusp proton aurora patterns in the northern hemisphere are shown for each model.*

servations also complement the TIMED observations of airglow that are made at higher spectral resolution but with limited spatial coverage from low Earth orbit.

Equatorial Airglow Bands. The IMAGE-FUV SI-13 instrument is now obtaining global-scale images of airglow emissions from the regions of enhanced ionospheric densities located to the north and south of the magnetic equator and extending from sunset towards the midnight sector. Decreases in the intensity of these equatorial airglow bands indicate the presence of plasma depletions ("bubbles" or "plumes") associated with equatorial spread-F. The IMAGE team has recently reported the first space-based FUV observations of these low-latitude plasma depletions and demonstrated a technique for determining their drift speed [*Immel et al.*, 2003]. Additional studies of these phenomena are planned for the 2003 and 2004 seasons and will complement other ongoing or planned activities such as ARGOS and C/NOFS that will monitor ionospheric irregularities (cf. *Bernhardt et al.*, 2001] as well as studies employing ground-based facilities such as the NSF radar at Jicamarca, Peru. By 2007, apogee will be back in the equator and IMAGE will again be able to make measurements of the equatorial airglow bands during solar minimum and make comparisons with our current observations during the declining phase of the solar cycle.

O/N_2 Ratio Imaging. Continued global scale observations of the brightness of the atomic oxygen emissions, and their variations during magnetic storms (cf. **Figure 8**) complement observations from the NASA TIMED mission, particularly the GUVI instrument. These measurements will provide validation for community atmospheric modeling efforts for geomagnetic events in the declining part of the solar cycle, which produce significant global changes in the distribution of thermospheric O and N_2 and in the height profile of thermospheric mass density and temperature. Studies of the global-scale development of thermospheric storms in both positive and negative ionospheric phases can effectively be pursued using global imaging of dayside 135.6-nm emissions with the SI-13 instrument. Comparisons of neutral density perturbations with results from general circula-

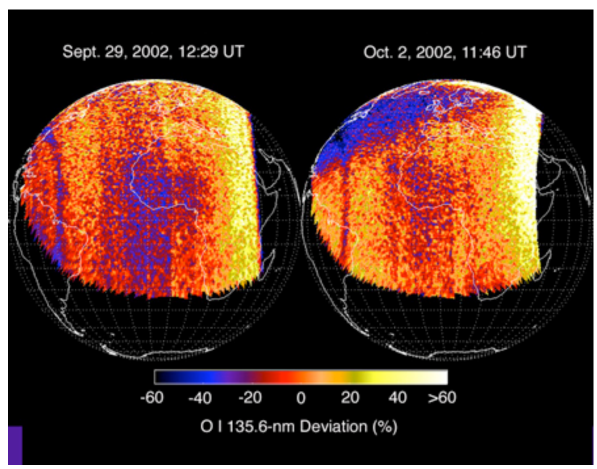

Figure. 8. *This image pair demonstrates the global redistribution of thermospheric oxygen before (left-hand image) and after (right-hand image) a magnetic storm, with increases in O relative to N_2 at low latitudes, and corresponding decreases at high latitudes. This change is reflected in the brightness of the 135.6 emission measured by SI-13, and variation from quiet-time average brightness is shown. IMAGE monitors these global variations, which have strong effects on ionospheric densities, for up to 8 hours per orbit, with a dedicated 135.6 channel. Modeling using the AURIC code [Strickland et al., 1999] allows the retrieval of O/N_2 estimates.*

tion models provide an important and unique validation tool for modelers.

B.5 Solar-Cycle Variation of Ionospheric Outflows

It is important to determine how ionospheric outflow, as measured through the terrestrial emission of LENAs, will vary over the current solar cycle. We believe that more or less constant electromagnetic coupling effects occur throughout the entire solar cycle, but that variations of solar UV intensity (and possibly energetic particles) modulate the temperature, scale heights, and therefore density profile of the thermosphere and ionosphere. It is known that the ion outflow flux is enhanced at solar maximum. However, the corresponding fast-neutral-atom emission has never been studied before IMAGE, and is relatively unexplored.

During the extended mission IMAGE will be in a good position to look at longer term variations both in the emission of relatively energetic LENAs to high altitude and in the creation and loss of the hot oxygen geocorona present at gravitationally trapped energies.

B.6 Subauroral Proton Arcs

Burch et al. [1985] and *Cowley et al.* [1991] published IMF B_Y-dependent convection and field-aligned current models showing a shift of the dayside auroral oval toward dawn for B_Y positive and toward dusk for B_Y negative. **Figure 9** shows the prediction of the Cowley et al. model, which is very similar to that of Burch et al. The proton oval should have a constant relationship to the open-closed field line boundary (dashed curve in **Figure 9**). The subsequent results of *Burch et al.* [2002] are consistent with these model predictions. Burch et al. noted that subauroral proton arcs in the afternoon sector appeared when B_Y changed from negative to positive. In this case the entire dayside proton oval shifted toward the dawn meridian revealing pre-existing proton precipitation from the ring current which, for B_Y negative, was hidden within the main oval precipitation. The models of *Burch et al*. [1985] and *Cowley et al*. [1991] further predict that the opposite behavior should occur in the southern hemisphere. That is, the afternoon-sector subauroral proton arcs should appear in the southern hemisphere when B_Y shifts from positive to negative. During 2005 and 2006, when apogee is above the south pole, IMAGE FUV SI-12 data will be used to test this prediction.

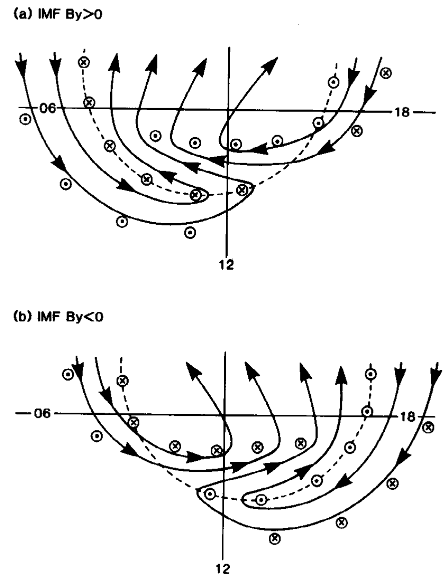

Figure 9. *Sketch showing the IMF B_Y-dependent effects on the streamlines (solid curves) and on the open-closed field line boundary (dashed curve) in the northern hemisphere. The circled symbols represent the FAC flow, circled dots represent upward current, and circled crosses downward current. (Top) B_Y positive, (Bottom) B_Y negative [Cowley et al., 1991].*

B.7 Dayside Subauroral Proton Flashes

Hubert et al. [2003] have reported a different type of subauroral proton aurora (**Figure 10**). Known as subauroral proton flashes, these emissions appear impulsively in response to solar-wind pressure pulses at dayside latitudes well below the main proton auroral oval. These shock-induced transient emissions develop with a time scale of a few minutes, and have a relaxation time on the order of 10 minutes. Magnetic field mapping implies that the flashes map to the region between the magnetopause and the Earth. The most probable precipitation mechanism is ion-cyclotron generated pitch-angle scattering, which is enhanced by the presence of cold plasma. To date there have only been a few cases during which plasmaspheric imaging was available, and the results are yet inconclusive.

Another unexplained aspect of the flashes is

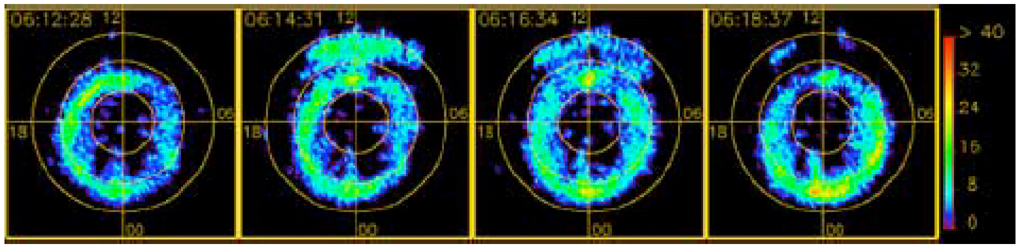

Figure 10. *SI-12 counts remapped in geomagnetic coordinates at two-minute intervals showing the subauroral proton flash of November 8, 2000 at 0614 UT. The background has been removed. Concentric yellow circles are 10° MLAT apart, noon MLT is at the top of each picture.*

that some pressure pulse events cause sub-auroral emissions, while others do not. During the extended mission, we will have the opportunity to observe pressure pulse events created from co-rotating interaction regions in the solar wind. Perhaps the way the pressure is induced on the magnetosphere affects the conditions for generating the ion cyclotron waves that cause the pitch angle scattering and precipitation. Since cold plasma density likely plays an important role in the instability, we will use combined FUV and EUV data (along with Los Alamos Geosynchronous Data) to determine which types of pressure pulse events are most effective in ring-current precipitation.

B.8 Proton Aurora and Plasma Sheet Dynamics

Østgaard et al. [2003] used conjugate auroral images from Polar and IMAGE to determine that IMF B_Y causes a shift in the local time of the substorm breakup arc that is opposite in the northern and southern auroras. In a similar vein, *Brandt et al*. [2002] have shown that IMF B_Y variations cause distortions of inner-magnetosphere convection electric field patterns and a resulting skewing of the local time of ring current injection. This skewing is directed more toward dawn as B_Y becomes more positive. Since the ring current images map to the equatorial plane relatively close to the Earth, they are expected to be conjugate (connected magnetically to nearly the same latitude and MLT in both hemispheres). The proton aurora imager responds to particles with much lower energies than those in the ring current, so it is not clear at what ion energy the conjugacy breaks down to produce the opposite B_Y effects in the northern and southern breakup aurora. Moreover, it is not known how the freshly injected and subsequently trapped ions of the plasma sheet follow the B_Y variations. A new analysis tool developed by the MENA team allows the proton aurora and the energetic neutral atoms to be tracked together over several hours to investigate and answer such questions. An example of the data produced by the MENA data analysis tool is shown in **Figure 11**, which shows the development of proton aurora emissions and ENA emissions as functions of MLT and UT. In each case the emissions are integrated over the full width of the proton auroral oval (in latitude for the proton aurora and in equivalent radial distance, or L-shell, for the ENA emissions). In the example shown in **Figure 11**, several different phenomena are seen to vary in concert in both types of emissions. For example, several “pseudo breakups” can be seen in both data sets between about 0930 and 1230 UT, and all are in the post-midnight region. A proton auroral breakup occurs at about 1245 UT, initially spanning the midnight meridian and then propagating rapidly toward dusk. The MENA data show a simultaneous enhancement, but it is more symmetric about midnight. In addition, while the proton aurora emissions decrease rapidly after breakup, the ENA emissions continue at a high level. This difference is probably caused by the intense fluxes of trapped ions that decay away slowly because of charge exchange.

By analyzing numerous substorms with various IMF directions in the northern hemisphere, it will be possible to determine the level of coherence between the proton aurora and the plasma-sheet injections. During 2005 and 2006 similar data will be obtained in the southern hemisphere allowing a determination of the degree of conjugacy of both of these phenomena.

B.9 Correlation Between Dayside and Nightside Reconnection

Lewis et al. [2003] have reported a distinct correlation between proton aurora “reconnection

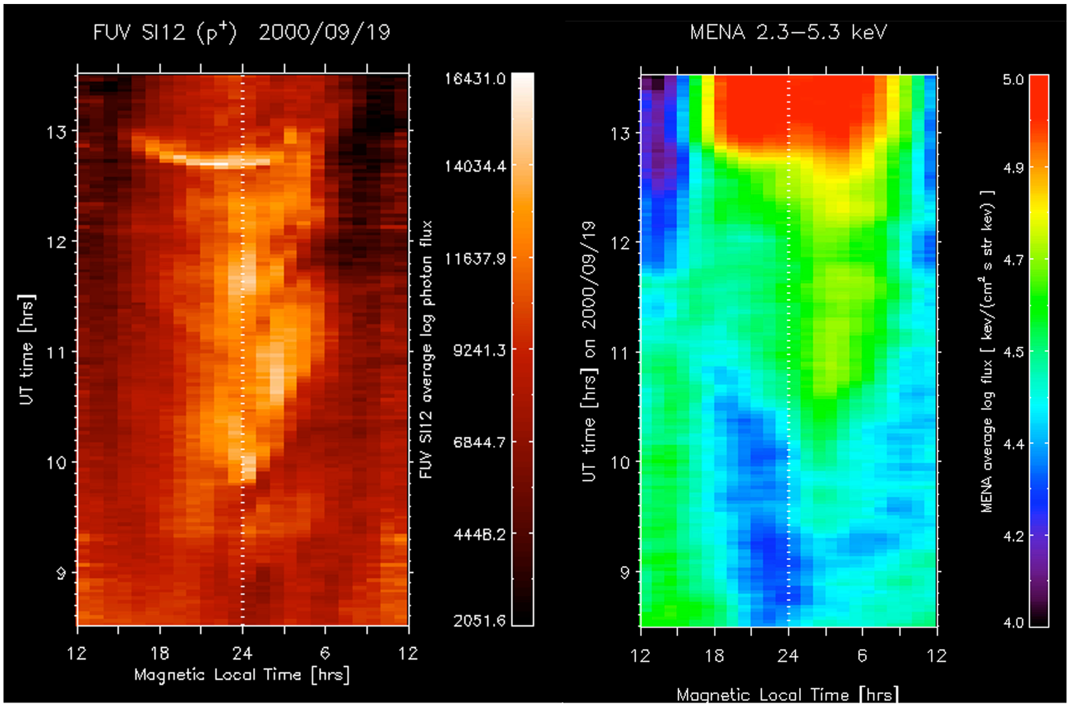

Figure 11. *(Left panel) Proton aurora intensity versus MLT and UT with each pixel integrated over the latitudinal width of the proton auroral oval at each MLT. (Right panel) Similar plot for MENA ENA data but with each pixel integrated over L shells corresponding to the proton auroral oval width at each MLT [Jahn et al., 2003].*

spots" [*Fuselier et al*., 2002a] on the day side and night side, which move together in response to changes in the IMF. An example of the dayside and nightside spots and a plot of their movement in local time are shown in **Figure 12**. When the IMF is northward, the "nightside" spot is located high in the polar cap but moves rapidly toward the night side as the IMF turns southward. At each time, the spot is located just on the closed field-line side of the open-closed boundary (as determined by the presence of proton aurora emissions), which bifurcates the polar cap from day to night. During this motion, there is a concurrent motion of the dayside spot from the morning side to the afternoon side as IMF B_Y is changing from negative to positive as shown earlier by *Fuselier et al*. [2002a]. The remarkable coherence between the two spots shown in **Figure 12**, which occurs within the two-minute interval between FUV SI-12 images, suggests that there was rapid communication between the dayside reconnection event and the nightside reconnection event. *Lewis et al*. [2003] suggest that this communication is by fast-mode Alfvén waves.

It is important to know the locations and motions of both the day and night side reconnection spots in the southern hemisphere for similar IMF conditions. This determination will be made during the extended mission between 2005 and 2006 when the IMAGE apogee is over the southern hemisphere. It is expected that the dayside reconnection spot's location in MLT with respect to the noon meridian will be mirrored in the northern and southern hemispheres, i.e., IMF $B_Y < 0$ is expected to cause a morning-side spot in the north and an afternoon-side spot in the south. The close correlation between the position of the dayside reconnection spot and the polar-cap/nightside spot suggests a direct control of both phenomena by the IMF, but it is not known whether the polar-cap/nightside spot shows the same type of mirror image between hemispheres or if it eventually becomes conjugate toward the night side. The proposed complementary study in the southern hemisphere should answer this question and lead to a better understanding of the global effects of reconnection between magnetospheric and solar-wind magnetic fields.

B.10 The Quiet-time Plasmasphere

The declining phase of the solar cycle will provide better opportunities for investigations of several newly-discovered aspects of the plasmasphere.

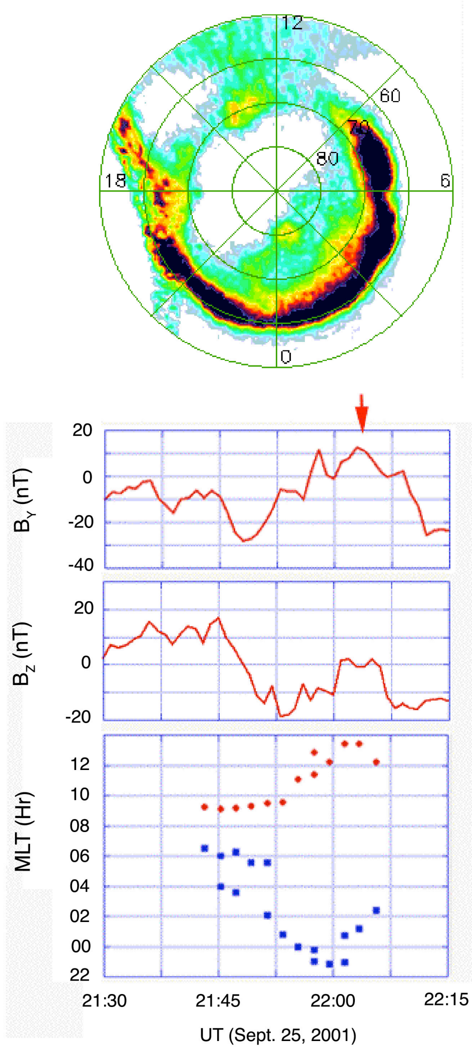

Figure 12. *(Top) FUV SI-12 proton aurora image on Sept. 25, 2001 showing a dayside reconnection spot at MLT~1330 Hrs and □~70° and a nightside reconnection spot at MLT~0100 Hrs and □~80°. (Bottom) IMF y and z components along with MLT of dayside (red) and nightside (blue) reconnection spots. Red arrow marks the time of the proton aurora image [Lewis et al., 2003].*

These aspects include corotation lag [*Sandel et al.*, 2003], plasmasphere He^+ refilling, interchange instability [*Lemaire and Kowalkowski*, 1981], and isolated plasmasphere erosion events [*Goldstein et al.*, 2003a].

Plasmasphere Corotation Lag. During quiet times, identifiable plasmaspheric features have often been observed to move with an angular velocity that lags corotation by 10-15% [*Sandel et al.*, 2003]. Magnetically quiet epochs will provide more opportunities to investigate this phenomenon and determine its source. This lag has not been predicted by any inner magnetosphere convection models, nor has there been any previous experimental evidence for it.

Quantifying the refilling rate of He^+. The EUV team has recently developed the capability to produce line-of-sight integrated column abundances of helium ions. This new quantitative capability can be used to measure the He^+ refilling rate. The declining phase of the solar cycle is an ideal time to study refilling, as there will be longer and more frequent intervals of deep quiet during which refilling will occur. Another advantage to studying refilling during 2004-2007 is that for much of this interval EUV will obtain images from a vantage point at lower latitudes, in many cases almost "edge-on." So far, we have mainly had a view of the equatorial distribution of cold plasma, but with the different perspective we may very well be able to observe the details of the process whereby plasma flows out of the ionosphere and gradually fills up magnetic flux tubes. This capability will be especially effective after 2006, when EUV will be looking in the generally antisunward direction, thus minimizing sunlight contamination during "edge-on" viewing. In conjunction with in situ data (from LANL geosynchronous satellites as well as IMAGE RPI), an EUV refilling study has great potential to advance our quantitative understanding of quiet-time plasmasphere dynamics.

The Possible Role of Plasma Interchange Motions. While the simple models of *Nishida* [1966] and *Grebowsky* [1970] are quite good at reproducing the coarser aspects of plasmaspheric dynamics; more sophisticated models have just begun to yield understanding about some of the mesoscale structure of the plasmasphere [*Goldstein*, 2002 and references therein]. However, the role (if any) of the interchange motion in plasmaspheric dynamics remains unknown. When the relatively dense plasma at the plasmapause moves in roughly circular paths, there is a weak tendency for the denser plasma to be flung outward owing to centrifugally-driven interchange instability. Along these lines, *Lemaire and Kowalkowski* [1981] suggested that the centrifugal interchange instability may result in a "tearing off" of plasma from the plasmapause. Although during active times enhanced ring current pressure probably acts to suppress the interchange instability at the plasmapause [*Huang et al.*, 1990], extended periods of quiet conditions may allow sufficient time for the weak interchange motion to have a significant impact on plasmaspheric structure. Suggestive of this possibility, EUV observations during quiet conditions often show a large plasmasphere with a great deal of azimuthal structure at about the theoretically expected scale size of structures caused by interchange motion. An extended mission into the declining solar cycle will provide more opportunities to study the role of quiet-time interchange motion.

Isolated Plasmasphere Erosion Events. *Goldstein et al*. [2003b] have used a plasmasphere erosion event imaged by EUV to determine that the direct cause of the erosion was a southward turning of the IMF and that the enhancement of convection electric fields in the inner magnetosphere lagged the southward turning by approximately 30 minutes. Further analysis of erosion events should provide even more information about the response of inner magnetosphere electric field and flow patterns to IMF variations. Quiet times, with isolated events, are much better suited for this investigation because during solar maximum individual events are often interrupted by more complex phenomena associated with major storms. The IMAGE extended mission during the declining phase of the solar cycle should provide numerous opportunities for research on the causes of plasmasphere erosion and on the global electric fields associated with them.

B.11 Magnetopause/Boundary Layer Dynamics

During the extended mission, the IMAGE orbit will consistently approach the magnetopause more closely than at any other time since launch. 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. The two seasons for which this configuration will occur are in fall 2003 and again in late 2007. With the apogee of IMAGE only a few R_E from the magnetopause, the density structure of the magnetopause boundary layer and the location of the magnetopause will be observed continuously for hours providing a wealth of information on this previously elusive boundary. RPI has already obtained a number of direct echoes from the magnetopause boundary layer. These echoes have required long integration times and have always shown a considerable amount of range spreading indicating rapid boundary motion and/or plasma density irregularities. Based on these previous observations, and the increase in density at the subsolar point, RPI will be programmed to make maximum use of this unique opportunity. With repeated observations of density profiles of the magnetopause boundary layer on minute time scales and over a time span of several hours, RPI should be able to see the evolution of boundary layer thickness on substorm time scales.

B.12 Magnetic Field Line Configuration

Under quiet conditions, a dipole model accurately describes the field line configuration below an L of 4 and is routinely used in the inversion of RPI echoes to obtain field line density profiles. However, approximately 20% of the ducted echoes observed by RPI, coming from the conjugate hemisphere, reveal that there must be large-scale field line changes. There are a number of possible explanations that are being investigated such as field line stretching, compression, or skewing. It is tantalizing to think that these changes coincide with ring current and other geomagnetic storm phenomena, but our current statistics are too low and the IMAGE ENA and FUV data are not always simultaneous. Observations for 10s of minutes to hours providing multiple sets of ducted echoes along the same L shell are necessary to distinguish between these explanations and to obtain the correlative data.

The IMAGE orbit since launch was designed to image the inner magnetosphere from a vantage point high over the polar cap. This has necessitated the orbit to cut through the mid-latitude L shells very quickly providing only one or two plasmagrams with the appropriate guided echo observations. With the orbit precession there will be times when IMAGE will move along or nearly along key L shells for much longer periods. There are two major seasons for studying field line configuration changes involving outer plasmaspheric, trough, and auroral zone field lines. These seasons are approximately six months long and are fall 2003 through mid-2004 (primarily the dayside magnetosphere) and the last six months of 2007 (primarily the nightside).

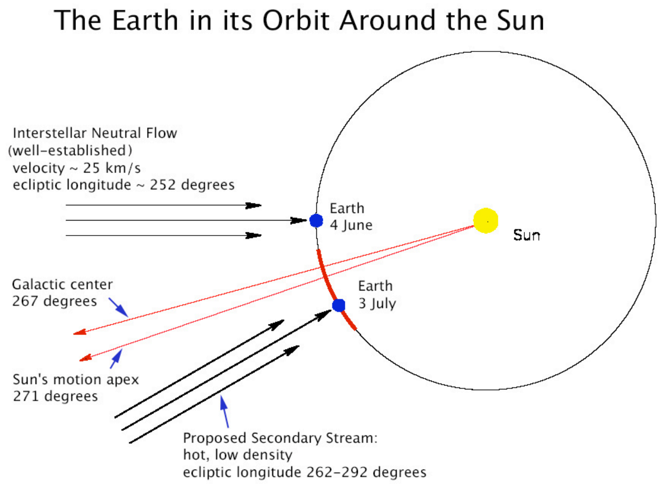

Figure 13. *Schematic of the Earth's orbit around the Sun illustrating the principal fiducial points and the proposed secondary stream of hot, fast interstellar neutrals inferred to be important in the inner heliosphere.*

B.13 ISNA Secondary Stream

The LENA instrument makes direct measurements of the interstellar neutral atom flow through the inner heliosphere [*Moore et al.,* 2003]. These observations originate during the winter season, beginning when the Earth passes across the interstellar neutral gas flow downstream line (2 Dec) and continuing as the Earth begins to turn upstream into that flow. At such times a combination of enhanced density and relative velocity make this weak flux visible. A density enhancement of He atoms is expected owing to their focusing by Solar gravity as they pass the Sun, and indeed this is seen to be the case for He^+ pickup ions formed from thermal He [*Gloeckler and Geiss*, 2001]. However, the inferred location of maximum LENA density for these fluxes is later by about 30 days than the passage of Earth through the downstream line, or the peak in the He^+ pickup ions. A recent analysis of variations of the direction of arrival of these neutrals [*Lennartsson et al.*, 2003] suggests that they are a combination of the known He focusing cone together with an inner heliospheric secondary stream of H that is shifted from the established thermal hydrogen arrival direction by ~30 deg, as illustrated schematically in **Figure 13.**

Multiple data sets are now being brought to bear on this problem. These include observations from other ENA instruments, observations of elevated cyclotron wave amplitudes driven by pickup ion distributions, and detailed study of ion pickup observations. With six data sets all pointing in a different direction from the established interstellar upstream direction, it seems clear that the LENA data set has surfaced a surprising new reality for interstellar medium interactions with the inner heliosphere, which we are eager to pursue in future years, through a complete solar cycle if possible.

C. Relevance to the Space Science Enterprise Strategic Plan

As shown in **Table 3**, IMAGE contributes to every goal of the NASA Space Science Enterprise 2000 Strategic Plan and contributes significantly to 70% of the enterprise objectives. One of the reasons for the broad relevance of IMAGE to the Space Science Strategic Plan is the fact that it is a multispectral imaging observatory that obtains rapid comprehensive views of the Earth's magnetosphere and ionosphere while also having the ability to view outward into the heliosphere and apparently even beyond. Because of its broad-based imaging capabilities, not only is IMAGE ideally suited for its own mission, but it also is a pathfinder for numerous other planned OSS missions including Interstellar Probe Pathfinder, Radiation Belt Mapper, Ionosphere Thermosphere Mapper, Stereo Magnetosphere Imager, and Geospace System Response Imager. All of these missions are either approved or hold a high priority in an SEC roadmap or the NRC Solar and Space Physics Decadal Study.

D. Relevance to the 2002 Sun-Earth Connection Roadmap

IMAGE contributes to every science objective in the Sun Earth Connection 2002 Roadmap (**Table 4**). There is a strong representation in each science objective, with contributions to two thirds of the research focus areas. The broad contributions result from several important aspects of the IMAGE mission. Among these are:

- IMAGE is the first "Space Weather Satellite" and is the only mission to obtain global multispectral images of the inner magnetosphere on time scales of a few minutes, which are relevant to the development of magnetospheric substorms and geomagnetic storms and are directly related to the flow of energy and matter in the magnetosphere

Table 3. *IMAGE contributions to the NASA OSS Strategic Plan are indicated by darker boxes.*

Enterprise Goals	Enterprise Objectives	IMAGE Contribution
Science Objectives		
Chart the evolution of the universe from origins to destiny and understand its galaxies, stars, planets, and life.	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 elsewhere 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.	
Education and Public Outreach Objectives		
Share the excitement and knowledge generated by scientific discovery and improve science education.	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.
Human Space Flight Objectives		
Use robotic science missions as forerunners to human exploration beyond low-Earth orbit.	Investigate the composition, evolution, and resources of Mars, the Moon and small bodies.	
	Develop the knowledge to improve space weather forecasting.	Nearly continuous multi-spectral imaging of geospace; real-time data link for NOAA.
Technology Objectives		
Develop new technologies to enable innovative and less expensive research and flight missions.	• 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, published, and applied to new missions (TWINS) and future mission concepts (GSRI in 2003 SEC Roadmap and SMI in 2003 SSP Decadal Study).

(science objective 1) and the societal impacts of solar variability (science objective 3).

• 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. The use of real-time data for space weather forecasts relates

Table 4. *Primary Sun-Earth Connection Science Objectives and Research Focus Areas (from the 2003 SEC Roadmap) along with proposed IMAGE contributions during an extended mission.*

Sun-Earth Connection Science Objectives	Sun-Earth Connection Research Focus Areas	IMAGE Contributions During Extended Mission
Understand the changing flow of energy and matter throughout the Sun, heliosphere, and planetary environments.	Understand the transport of energy and matter within the Sun, the solar atmosphere, and into the solar wind.	
	Determine the evolution of the heliosphere and its interaction with the galaxy.	Improve statistics of upper limit on ENA flux from the termination shock during solar minimum. Search for interstellar neutral H during solar minimum.
	Understand the response of magnetospheres and atmospheres to external and internal drivers.	Determine global response of the magnetosphere and plasmasphere to CIR shocks during solar minimum. Determine solar-cycle dependent ionospheric ion outflow.
Explore the fundamental physical processes of plasma systems in the solar system.	Discover how magnetic fields are created and develop and how charged particles are accelerated.	Verify reconnection picture of the cusp from southern hemisphere proton aurora. Combine in situ and imaging data to determine the importance of anti-parallel versus component reconnection.
	Understand coupling across multiple scale lengths and its generality in plasma systems.	
Define the origins and societal impacts of variability in the Sun-Earth Connection.	Develop the capability to predict solar activity and the evolution of solar disturbances as they propagate in the heliosphere and affect the Earth.	Only monitor of global effects of solar disturbances on the magnetosphere and plasmasphere.
	Develop the capability to specify and predict changes to the Earth's radiation environment, ionosphere, and upper atmosphere. Understand the role of solar variability in driving global change in the Earth's atmosphere and in controlling long-term space climate.	First and only real-time monitor of the high-latitude ionosphere proton and electron precipitation. Global ionospheric airglow measurements at low latitudes supporting LWS missions.

directly to the societal impact of solar variability (science objective 3).

- 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. Continuous global auroral imaging, especially over substorm timescales (~1 hour) and over longer storm timescales (~days, with brief interruptions during perigee passes) has been shown to be an important component for determining the flow of energy and matter in the magnetosphere (science objective 1).
- IMAGE provides the only images of the global distribution of proton precipitation, including precipitation in the cusp due to magnetic reconnection. The investigation of magnetic reconnection is directly related to the study of fundamental plasma processes (science objective 2).
- 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 and is directly related to the flow of energy and matter in the magnetosphere (science objective 1).

E. Technology Development for Future Missions

IMAGE contributes heavily to technology development for future SEC missions. Imaging techniques pioneered by the IMAGE mission will be incorporated into future SEC missions, and analysis techniques pioneered by IMAGE will be critical for understanding future remote sensing missions. Three examples of new technology development for IMAGE during the new mission are:

E.1 Imaging of Planetary and Interstellar Energetic Neutral Atoms

IMAGE has already provided an important upper limit on the flux of ENAs from the heliospheric termination shock (believed to be ~100 AU from the Sun) [*Roelef et al.,* 2003b]. During the new mission, additional observations will be made in directions currently not available (due to blockage by significant background sources such as the Sun and the Earth). These new observations made by LENA, MENA, and HENA will provide important pioneering measurements for future missions that will be dedicated to interstellar ENA imaging. These missions include the Heliospheric Imager and Galactic Observer (HIGO), an intermediate term (2007-2012 start) mission identified in the 2002 Roadmap to determine the nature, size, and variability of the heliospheric boundaries and the composition of interstellar gas through a combination of in situ and ENA imaging observations.

E.2 Tomographic Imaging of the Earth's Magnetosphere

The first of the Two Wide-angle Imaging Neutral Spectrometers (TWINS-1) will be launched in 2003, with the second launched in 2004. These missions carry ENA imagers nearly identical to MENA. The combination of IMAGE and TWINS will allow tomographic imaging of the Earth's magnetosphere a year in advance of the TWINS-2 launch. This will allow development of tomographic inversion techniques prior to the launch of TWINS-2. When TWINS-2 is launched, IMAGE will provide a third view angle for tomographic inversion. This combination will provide a precursor for multi-spacecraft imaging missions.

E.3 Radio Tomography

High-frequency transmissions of RPI in the sounding mode, when received by the plasma wave instruments on remote spacecraft such as Wind or Cluster, are now providing a new opportunity to test the feasibility of radio tomography as a possible imaging technique for use on upcoming constellation missions [e.g. *Ergun et al*., 2000]. *Cummer et al*. [2001] and *Cummer et al*. [2002] have published the results from a series of single and multi-frequency emissions by RPI on IMAGE, with receptions by the Waves instrument on Wind and the Wideband instrument on Cluster. Tests during the new mission will use multi-frequencies transmitted by IMAGE and received by the Cluster spacecraft. Radio tomography inversions on these data will be pioneered to determine the Faraday rotation and the phase, which provides the density structure and magnetic field and direction in the image plane.

F. Cooperative Research with Other Missions, Ground-Based Facilities, and Modeling

IMAGE has participated in many joint studies with other space missions and ground-based facilities as well as with several global modeling groups. Some examples of these collaborations are as follows:

- *Goldstein et al*. [2002] used the Rice Magnetospheric Specification Model (MSM) to determine the cause of plasmasphere shoulders as south-north transitions of the IMF.
- *Phan et al*., [2003] used IMAGE FUV SI-12 data to confirm that Cluster had crossed a northward-IMF reconnection event as indicated by the in situ data.
- *Baker et al*. [2002] used IMAGE FUV and HENA data to relate Cluster data during a magnetic storm to the global magnetospheric response.
- *Burch et al*. [2002] used DMSP and LANL Geosynchronous data to relate proton precipitation and plasmaspheric tail occurrence to the subauroral proton arcs observed by IMAGE FUV SI-12.

- *Foster et al.* [2002] used IMAGE EUV data to establish the direct magnetic connection between plasmaspheric tails and plumes of high total electron content observed by the Millstone Hill radar and by GPS receivers.
- *Cummer et al.,* [2001; 2002] used IMAGE RPI transmissions with reception by the Wind spacecraft and with the Cluster spacecraft to measure Faraday rotation testing the feasibility of radio tomography for future missions.
- *Green et al.*, [2003] compared IMAGE EUV data of notch structures in the plasmasphere with Geotail observations of kilometric continuum to determine the averaged location of the source region and emission beam characteristics.
- *Dent et al.*, [2003] used IMAGE RPI and EUV data with coordinated ground-based magnetometer arrays SAMNET, IMAGE, and BGS to validate the cross-phase technique for determining the cold plasma mass density in the plasmasphere during quiet times.

Numerous other examples of close cooperation with other missions and activities could be noted to date and this type of cooperation is expected to increase rapidly during the IMAGE extended mission.

II. Technical and Budget

A. IMAGE Technical Status as of 30 April 2003

A.1 Instruments

After 3 years of operation, all of the IMAGE instruments continue to perform nominally. The technical status of each instrument is summarized below.

FUV. The FUV imagers are monitored weekly by taking images of known stars. **WIC:** Over the last 3 years, the sensitivity of the WIC microchannel plate (MCP) has experienced some degradation but remains within planned range. To compensate for the sensitivity loss, we have raised the MCP high voltage by 25 volts, from 1100 V to 1125 V. Given the rate of degradation and the available tested high voltage overhead, we expect that the WIC instrument can operate with three more such adjustments, providing a projected instrument life at full performance for six more years. **SI**: SI shows a larger-than-expected response to temperature changes. Especially at instrument temperatures above 20 degrees C the sensitivity of the SI drops, most likely because of changes of preamplifier performance. We try to counteract such changes by careful operation of instrument heaters and adjustments of instrument high-voltage and pulse thresholds. Remaining sensitivity changes are corrected in the ground data analysis software by monitoring the instrument response to light input from stars. **GEO**: So far, we have not seen any obvious change in instrument performance of that channel.

EUV. The performance of EUV has been nominal since its first turn-on. The version of the flight software loaded when the instrument was delivered is still in use.

The sensitivity of EUV has been stable in flight. We monitor the sensitivity by observing the Moon, a relatively bright and stable source of reflected sunlight at 30.4 nm. These observations are the best available measure of end-to-end performance. After accounting for variations in the solar flux at 30.4 nm, we find no evidence for a change in sensitivity.

We have adjusted the high voltage to the MCP detectors to keep their gains within the acceptable range. We monitor the gains of the MCPs by measuring their pulse-height distributions continuously. As expected, the gains at a constant voltage have decreased slightly with time. In September 2000 and in July 2002, we increased the high voltage to the detectors to compensate for this drop in gain. Because the modal gain is much higher than the counting threshold, the changes in gain were not reflected in variations in sensitivity. At the present rate of gain decay, the HVPS has reserve capacity sufficient for many years of normal operation. Apart from these planned changes, the output of the HVPS has been stable, and free of secular drifts.

In late January 2003 we detected an increased response to scattered light in EUV's center camera under some conditions. At the same time, that camera began responding to a few of the brightest stars in the FUV spectral range. The most likely explanation is the formation of a hole in the entrance filter. Using the known flux from the detected stars, we estimate the diameter of the hole to be ~100 microns. The effect of the hole is to increase the background when the EUV field is near the Sun. The increased background does not normally interfere with the operation of the camera.

HENA. The HENA instrument continues to perform nominally, producing data that meet the IMAGE science requirements for ENA imaging. HENA routinely produces images in 9 energy bands (covering 10 keV to 200 keV) for hydrogen ENA and six energy bands for oxygen (covering 30 keV to 220 keV). HENA has shown few signs of degradation over the three years in flight. The MCPs, after a series of voltage increases during the first year and a half, have reached their stable gain state, and we have not had to raise the voltage on them since 2001. They are manufactured using a process that prevents them from degrading with throughput, and we expect them to continue to perform adequately for an indefinite period of time. The HENA high voltage ion rejection plates have remained biased at the same level since the instrument was commissioned, and we have seen no indication of degradation of this important subsystem. Because these are the sensor components most subject to aging, and given the fact that we have seen no evidence for degradation due to accumulated radiation dose in the HENA electronics, we expect HENA to continue to return high-quality ENA images for the indefinite future.

MENA. MENA instrument health is generally excellent. The detector voltages require occasional increase, but we have plenty of margin. The MENA detectors are holding up well, and have not been loaded beyond a small fraction of their expected lifetimes. The collimator in Sensor 1 has shown a gradual degradation in performance over the last year, probably due to a sputtered resistive buildup on the insulating standoffs. This has the effect of increased noise background due to reduced suppression of local hot plasma. Though the effect is now noticeable, it is by no means debilitating at this time. Should it prove necessary to do so, MENA can be re-configured to a two-headed mode, with concomitant telemetry re-allocation. The MENA carbon foils (C-foils) show no sign of degradation, as demonstrated by large (~0.5) valid/stop ratios, a direct measure of the efficiency C-foil (Start) emission and detection.

LENA. The IMAGE LENA Imager continues to return excellent quality low-energy neutral atom data in an energy range (few eV to few keV) that has never before been explored from Earth orbit. LENA appeared to lose its neutral atom conversion efficiency gradually during 2002, despite the steady dipping of the IMAGE perigee below 1000 km altitude. Perigee passes play a role in refreshing the coating of atmospheric atoms that form the active LENA conversion surface as an atomic layer on a polished Tungsten surface. Checks to see if the MCP detector gains were responsible for the appearance of efficiency loss were initially negative and were thought to confirm the hypothesis of conversion surface degradation. However, further testing a few months later revealed significant MCP gain loss. This was corrected by an upward detector bias command on 6 March 2003. To counteract such gain loss, the LENA team has developed a procedure for diagnosing this condition and setting new gain levels, which will be periodically implemented in the future.

RPI. The performance of RPI has been nominal since it was first turned on with the exception of losing a redundant transmitter on May 8, 2000. RPI has suffered 4 single event upsets with the instrument always returning to its nominal state after being reset. RPI uses 6 antenna elements in a 3-axis orthogonal configuration feeding 3 receivers. The X and Y-axis antennas, originally extended to 500 m tip-to-tip have suffered debris collisions with the –X antenna losing ~130 m on October 3, 2000 and the +Y axis antenna losing a small part of the antenna (possibly only the tip mass) on September 18, 2001. The 20 m Z-axis antennas have remained unaffected. Currently RPI transmits with full power on the +X antenna, and partial power on the –X antenna, and receives on all 6 antenna elements. The estimated loss to the science objectives based on the resulting shorter antennas has been minimal. All prime mission science objectives from RPI have been met.

CIDP. The CIDP is continuing to function as designed. Early in the mission, two patches were applied to its software in order to correct calculation errors in the Time-Attitude Synchronization software. A third patch allows us to disable the TAS software from safing the payload in the event that strict attitude knowledge is not available. CIDP has rebooted itself twice, in response to suspected memory hits. The most recent of these was in February 2003, and the reboot process and operations since then have been nominal. In addition, SCU powered off CIDP during the recent eclipse season. Again, recovery has been nominal.

CIDP control of payload deck heaters was instrumental in our approach to the extremely long eclipses experienced during the first part of April

2003. The eclipses were caused by the precession of the apogee down to the plane of the ecliptic for the first time. Eclipse duration went from appx. 60 minutes (longest during the primary mission) up to 138 minutes worst case during this season, well beyond the design operating point of the system. The spacecraft power and thermal systems were stressed quite heavily, but we were able to survive the worst of the season without allowing payload temperature excursions significantly beyond the design survival limits. CIDP was re-booted twice during the season and SCU once, owing to excessive demands placed on the power system by the thermal control system, but in each case the safing macros worked as designed and allowed the system to recover to a safe condition without exceeding payload thermal limits. In addition, the experience gained has allowed us to work out control algorithms which should allow us to avoid such demands during the next such season, which will be in Autumn 2006.

A.2 Spacecraft

The spacecraft systems, despite their current stressful environment, appear to be continuing to function well. SCU rebooted on April 8 due to either a low-voltage or a low-battery condition resulting from eclipse-related heater demands, but the reboot sequence shed loads to allow the power system to recover. The GSFC Flight Operations Team has derived a work-around to correct the Mass memory Module (MMM) overwrite problem which continues to occur every few months. The work-around involves on/off cycling of the MMM every pass when the problem occurs. The lost data are recovered from the real-time data, which are held on line until reception of the store-and-forward data is verified. Beginning in FY2004, a southern-hemisphere station will be needed to receive the real-time data. Possible sites have been identified.

The attitude control system is responding very well and keeping the spacecraft within its attitude requirements despite the asymmetrical loss of RPI wire antennas. As from the first year, the AST is not functional during the summer months when its FOV is close to the Sun, but the Sun Sensor continues to provide reliable data during this period. We also run the torque rod in self-heat mode each winter to prevent its going to a temperature lower than its rated minimum. Part of this winter's run was at a lower current in response to larger dynamics caused by the reduction in stability associated with the lost antenna segments.

The EPS system continues to supply power above its design specifications, enabling us to remain power-positive during the eclipse. The array supplies approximately 12.5 Amps fully loaded, enough to run the spacecraft, payload, and a fraction of the heaters simultaneously, or to run the spacecraft, payload heaters, and simultaneously charge the battery from 40% to full state of charge (SOC) in less than 10 hours. The battery continues to maintain the bus in the specified voltage range down to a calculated SOC of 40% with the spacecraft systems all running (except the AST).

The communications system has performed flawlessly, enabling us to establish downlink and uplink often with 26-m DSN antennas, which provide greater flexibility than the 34-m antennas for which the system was designed.

The thermal system continues to be very efficient at dissipating heat from the payload and spacecraft systems. Although we anticipate degradation of the system as the thermal surfaces weather, this will actually be something of a relief as most of thermal-control challenges we have seen so far have been near the cold end of the scale (as detailed above).

No problems are apparent which would prevent continued operation of the IMAGE observatory for the foreseeable future. The final limit to operability will likely be solar cell degradation, but at the current rate that will not impinge on instrument operations for at least another 10 years during most seasons. Extreme conditions (eclipse operations, cold season) may be an exception to this, but that depends on the competing degradation of the solar arrays (which supply heater power) and the thermal control coatings (which remove heat).

A.3 Ground System: IMAGE Science and Mission Operations Center

The IMAGE Science and Mission Operations Center (SMOC) continues to operate extremely efficiently, performing spacecraft commanding and data acquisition, all data generation through Level-1, and rapid data delivery to the instrument teams and NSSDC for archiving. The data are 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. 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 are transmitted to the SMOC, where they are 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.

The IMAGE spacecraft engineering data are managed much like that of the science data since these data are written as CDF files and delivered to the National Space Science Data Center (NSSDC) and loaded into the Coordinated Data Analysis Web (CDAWeb) system within 48 hours after they have been generated. In this way the power of the CDAWeb system is used to do trend analysis for the health and safety of spacecraft and instruments and has been used extensively for anomaly resolution. All IMAGE sustaining engineering activities from Lockheed Martin (Sunnyvale) and SwRI (San Antonio) are performed rapidly and effectively by providing the necessary engineering data from CDAWeb. All of these innovative approaches to mission operations as implemented by IMAGE make it one of the most cost-efficient mission operation systems at GSFC.

B. Data Availability and Dissemination

B.1 The IMAGE Data System

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 the IMAGE team members as well to the entire science community and the public at http://150.144.211.77/image/image_main.html. Level-0 IMAGE data are typically used only by the IMAGE instrument 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 instrument teams and any other scientists who want to analyze IMAGE data. Casting the Level-0 IMAGE data into UDF provides a number of important benefits to the science community. Specialized software has been developed for analyzing the UDF data (see below) and enables the user to apply the latest instrument calibration and to inter-compare data from all the IMAGE instruments.

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 science 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 science and engineering data), IMAGE data products are easily available to the entire international science community. The NASA data availability catalog provides the archiving status of the IMAGE data.

The IMAGE team has gone to great lengths to include data analysis software with the IMAGE data. The IMAGE Software Suite (ISS) is accessible on the Web to the entire science community at http://image.msfc.nasa.gov/ and is also linked from the SMOC and IMAGE Science Center web pages, and has been distributed on CD-ROM at a number of AGU meetings. 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, Apple/Macintosh (OS X), and Linux/Unix platforms.

B.2 Distribution of IMAGE Data by Individual Instrument Teams

Each IMAGE instrument team maintains a web site from which different data products (e.g., custom plots/images generated with web-based image-making tools, quick-look/survey data) are available to the scientific community as well as to the general public. In addition to data products, these sites provide documentation, instrument-specific data analysis tools, and links to the IMAGE Data Delivery System at the SMOC, IMAGE Software Archive at the Marshall Space Flight Center and IMAGE Science Center web sites. The individual instrument sites also include resources such as publication lists, images or movies highlighting certain events, etc. All IMAGE web sites are multiply interlinked so that visitors to one site can find their way easily to other IMAGE sites of interest.

EUV. The primary EUV image analysis tool, *euv_imtool*, is available to any interested researcher at the EUV web site http://euv.lpl.arizona.edu/euv. This tool retrieves data from the UDF database and performs a variety of analysis tasks. Because it runs under IDL, it can be used on Windows, Mac, and Unix/Linux platforms. As a convenience to those who prefer not to install the UDF software and data files, *euv_imtool* also reads image files in Flexible Image Transfer System (FITS) format. A page on the EUV website can be used to request FITS files from the UDF database. Requests are processed automatically and the resulting FITS files stored for retrieval by ftp. Other data products are available at the EUV website, including selected single frames and more than 1400 movies, each made up of frames from a single IMAGE orbit.

FUV. The FUV web site http://sprg.ssl.berkeley.edu/image/ provides thumbnail-sized summary WIC images for almost the entire three years of the IMAGE mission. (The first date for which summary images are available is 18 May 2000.) In addition, the site now offers a WEB tool that allows anyone to access all of the image data from all three imaging channels. Using this tool, requesters can scale the images by adjusting the dynamic range and color table of the image. This option allows any scientist to generate publication-quality images directly from the FUV website by running a java program on the FUV team's server.

HENA. The HENA website http://sd-www.jhuapl.edu/IMAGE/ includes links to a broad variety of HENA browse products and to a web-based, menu-driven software package that can be run by any interested individual, allowing access to the HENA data using the same (fully documented) software tool that the HENA team uses for its custom viewing of HENA images [http://sd-www.jhuapl.edu/IMAGE/xhena2.html]. HENA data have been used in support of many science publications, and other researchers have often begun their analysis from these web-based resources, without need to make a request for data from the HENA team. The HENA data are among the most accessible to the larger community among currently active spacecraft data sets.

MENA. The MENA web site (http://pollux.space.swri.edu) provides a web-based image making tool, the MENA Image Making Engine (MIME), which allows users to make both custom images and movies. MIME gives full access to the MENA team image-making capabilities. The MENA web site also makes available pre-processed 24-hour summary plots of science and housekeeping data. Selected software products, including MENA image-making software, can be downloaded from the MENA site. All MENA software uses UDF data as input and is written in IDL, giving access to MENA data on all platforms on which IDL and UDF can be installed (Unix/Linux/Windows/Mac OS X). The MENA image making software is currently being used at the University of West Virginia, Auburn University, and the Rutherford Appleton Lab in the UK. All researchers are encouraged to use the MENA website for access to the latest version of MENA processing software.

LENA. The LENA primary analysis software retrieves data from the UDF database and performs a variety of analysis tasks. It is available to any interested researcher at the LENA web site http://lena.gsfc.nasa.gov. Because it runs under IDL, it can be used on Windows, Mac, and Unix/Linux platforms. For those who prefer not to install the UDF software and data files, the LENA data server provides a web-form-driven interface to the LENA software. The Custom Plots page on the LENA web site can be used to select from a wide variety of plot styles and to choose an arbitrary time interval. Requests are processed automatically, and the resulting plots and corresponding text data files are presented in a script-driven web page, made available for download in various formats, and stored on disk temporarily for retrieval by ftp. Many other data products are available at the LENA website, including standard summary plots in a number of different formats for all the data that have been acquired.

RPI. An expert database for cataloging and characterizing RPI echoes in the plasmagrams is operational at University of Massachusetts, Lowell http://ulcar.uml.edu/framesRPI.htm. Currently, there are 69 individual users from 20 institutions who actively participate in RPI data analyses, accessing the RPI database using the RPI software suite. Daily spectrograms are available at the IMAGE Science Center web site http://image.gsfc.nasa.gov/rpi/spectrogram. With the exception of the inversion routine (which is undergoing evolution toward an open software system within the next year) and software unique to individual studies, the RPI team uses the same analysis tools as those posted on the web at the IMAGE Software Archive (http://image.msfc.nasa.gov). The RPI team continues to reach out to the science community for collaborations and are very responsive to helping the community in getting access to the RPI data. Arguably, RPI data are the most complicated radio and plasma wave data ever generated by a spacecraft. The team has dedicated a significant amount of time to providing rapid access to the RPI data and analysis software tools. The team has also made its science expertise available to support community studies and inquiries.

B.3 Real-time Data Dissemination

Although the IMAGE mission primarily transmits data in a store and forward mode with two downlinks 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 or did capture IMAGE real-time data. These include: University of California, Berkeley (UCB) and the Communication Research Laboratory (CRL) in Japan. UCB no longer tracks IMAGE since its facility now tracks RHESSI. CRL uses IMAGE data for their space weather forecasting in Japan; both real-time FUV/WIC aurora images and EUV plasmasphere images are available at the CRL's web site http://www2.crl.go.jp/uk/uk223/IMAGE/index.html . 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. Owing to the important role that the IMAGE data has played in operational space weather forecasting, NOAA is currently seeking an organization that would be willing to track IMAGE while it is in the southern hemisphere in order to continue flow of IMAGE real-time data.

B.4. IMAGE as Part of the SEC Data Environment

The SEC data system is rapidly evolving to meet community expectations for an environment that will allow scientists to access SEC data "seamlessly," at various resolutions from multiple missions/sources, and then be able to apply a standard library of analysis tools. The IMAGE team recognized this need early and developed a data system that:

- allows the SMOC pipeline processing system to feed IMAGE data products directly into the long-term and active archive on a daily basis;
- makes its browse products immediately available through the CDAWeb system to promote inter-comparison with other SEC data;
- maintains an open library of tools and documentation used to analyze IMAGE data at its highest resolution.

Combined with IMAGE's open data policy, all these actions have leveraged aspects of the existing SEC data infrastructure to provide the best possible environment for facilitating multi-mission data comparison and analysis while integrating IMAGE with other existing SEC data.

C. Budget

C.1 In-Guide Scenario

The in-guide IMAGE budget for FY 03 is equivalent to the guideline provided as a result of the 2001 Senior Review. Even though IMAGE was the highest-rated mission in that review (**Table 5**), the FY 03 guideline was below the bare bones budget that was submitted. It represents a 40% decrease from the FY 02 budget, which has caused serious difficulties in operating the spacecraft, responding to anomalies, commanding the instruments, processing and archiving the data, responding to community requests for data, and still managing to achieve a meaningful science return. Most instrument teams were able to carry over some funds from FY 02 to lessen the impact, but these funds have been depleted. Thus the rest of FY 03 will place IMAGE in a below-bare-bones budget situation, which eventually will lead to a science program that is either severely atrophied across the board or which experiences the complete elimination of some activities, such as theory and modeling or one of the instruments. In view of the high scientific productivity of IMAGE and the excellent status of the spacecraft and instruments, either action is clearly unwarranted.

The further budget cuts from the planning guidelines FY 04 and FY 05 established after the 2001 Senior Review have now been exacerbated by even larger cuts. The guidelines for FY 06 and 07 bring the IMAGE budget to levels less than 50% of the FY 02 amount, before inflation. At these levels, very little science can be done, and very little support to the community of guest investigators and collaborators from other missions will be possible. The budget will be largely committed to operating the spacecraft, monitoring the health of the instruments, and processing and archiving data. Since graduate students can scarcely be supported with such an activity, the support of the various co-investigator universities will be in serious jeopardy.

Table 5. *Grades for science impact and NASA relevance of SEC satellite missions [**FINAL REPORT, Senior Review of the Sun-Earth Connection Mission Operations and Data Analysis Programs**].*

Satellite Mission	Science Grade	Relevance Grade
Geospace		
IMAGE	8.25 ± 0.71	8.71 ± 0.95
Cluster	8.00 ± 0.98	8.71 ± 0.95
Polar	6.75 ± 1.39	6.86 ± 1.46
FAST	5.88 ± 1.46	5.75 ± 1.49
Geotail	5.13 ± 1.96	5.50 ± 2.07
GGS Theory	4.38 ± 2.39	4.50 ± 2.67
SAMPEX	4.13 ± 1.25	5.38 ± 1.69
Solar-Heliospheric		
SOHO	8.00 ± 0.93	8.50 ± 0.53
ACE	7.00 ± 1.60	8.75 ± 1.16
Voyager	6.63 ± 1,85	7.38 ± 1.30
Ulysses	6.50 ± 1.77	7.00 ± 1.77
TRACE	6.13 ± 1.13	6.50 ± 1.51
Yohkoh	5.25 ± 1.49	6.13 ± 1.25
Wind	4.38 ± 1.41	4.88 ± 2.10
IMP-8	3.13 ± 0.35	3.63 ± 1.77

C.2 Requested/Optimal Scenario

We are submitting a requested/optimal budget for FY 04-07 of $5M/yr. Although there will be no increase for inflation, a budget at this level will allow IMAGE to continue its core activities, support the community of guest investigators and collaborators from other missions, and achieve a minimum level of meaningful science results.

In addition, in the Tracking and Data Acquisition category, we have added an amount of $100K/year to support the southern-hemisphere acquisition of real-time IMAGE data. Such reception is desirable for the continued space-weather monitoring activities of NOAA and is essential for backing-up the primary IMAGE store-and-forward data system. A software error allows the overwriting of science data with spacecraft data, and such overwriting has occurred every few months of IMAGE operations with a duration of a few days. During these times, much of the stored IMAGE data are essentially useless. However, the real-time data are not affected, and they are retained on line until the store-and-forward data are received and verified by the SMOC. He loss of data resulting from this problem has been minimized by on/off cycling of the MMM every orbit when it occurs. To change the flight software to correct the data overwrite problem would be very expensive and sufficiently risky that it is not recommended by the spacecraft contractor, Lockheed Martin Missiles and Space Co.

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III. Education and Public Outreach

The IMAGE Education and Public Outreach component is called POETRY (Public Outreach, Education, Teaching and Reaching Youth) (http://image.gsfc.nasa.gov/poetry). POETRY produces high-quality, innovative education products that explain space physics concepts to teachers and students in the K-12 community, participates in teacher training, and communicates the latest insights from IMAGE to the general public. POETRY meets the requirements of NASA education programs, as described in a recent address by Dr. Clifford W. Houston, the Deputy Associate Administrator for Education Programs. **Table 6** lists these requirements and demonstrates how IMAGE satisfies them.

A. Accomplishments

IMAGE Educational Products. IMAGE/POETRY recently collaborated with NASA/LRC on a NASA/CONNECT educational television program, "Dancing in the Night Sky," which discusses auroral science and IMAGE's role in exploring auroral physics. The program, which was shot on location in Norway and featured IMAGE/POETRY as the co-host, was televised on April 10, 2003 and was seen by over 300,000 teachers and over five million students nationwide. In 2002 IMAGE also collaborated with NASA/CONNECT in the program "Having a Solar Blast," which reached seven million students and 330,000 teachers. This video is being used in the Rice University ASTR 202 course and in "Sun-Earth Day."

We have completed two new education products: (1) "Exploring the Northern Lights" and (2) 32 one-page math and science problem sets. Activities developed for "Exploring the Northern Lights" were used in the NASA 2003 Sun-Earth Day national education and outreach event. We also provided the content for the OSS/SECEF (Sun-Earth Connection Education Forum) Student Observation Network's magnetometer program, which used the IMAGE/POETRY Soda Bottle Magnetometer to track geomagnetic storms during the 2003 Sun-Earth Day. We will continue developing and refining the one-page math and science problem sets through classroom testing during fall 2003.

Through its collaboration with SECEF, IMAGE/POETRY has been able to distribute its education products to over 50,000 teachers at national conventions and NASA-sponsored teacher training workshops. IMAGE/POETRY-developed products include the POETRY web site with 50 downloadable classroom activities in space science, an award-winning education video "Blackout," contributions to planetarium shows, and the Space Weather CD-ROM, which has been identified as an Exemplary OSS Education Resource (IMAGE/POETRY-developed educational material about the aurora has also appeared as supplementary material on the DVD release of the motion picture *Frequency*.) Another product is a sample page for undergraduate astronomy texts correctly describing the magnetosphere and the origin of aurora. This page was developed to rectify the misconception, found in most such texts, that the bulk of the auroral emissions are excited by solar wind particles impinging directly on Earth's upper atmosphere. Copies of this page have been sent to the

Table 6. *IMAGE-POETRY fully meets NASA Education program requirements.*

Requirements	IMAGE-POETRY Qualities
Customer focus	POETRY meets educator needs with K-12 curriculum development and teacher workshops.
NASA content	SEC focus, with explanations of magnetic fields, charged particles, the aurora, and IMAGE discoveries related to these phenomena.
Contribution to the NASA education pipeline	Teacher training in space physics concepts, development of elementary and secondary science curricula, inputs on magnetospheric and auroral science for astronomy textbooks.
Diversity	Teacher training and school workshops have involved numerous ethnic groups including Alaskan native Americans.
Evaluation	POETRY has received numerous awards from NASA, educational organizations, and the media. Received "exemplary" status from formal evaluation panel.
Sustainability	The products developed by POETRY are inserted into the Sun-Earth Connection Education Forum and the National Space Science Data Center. Distribution by NASA CORE allows some revenue to continue distribution of CD-rom's.

authors of astronomy textbooks. For educators and the general public, POETRY has produced a growing archive on its web site of significant IMAGE "**Discoveries**." Each "Discovery" presents a short abstract of a recent IMAGE result, along with an appropriate image that graphically highlights the discovery and gives links to additional resources (**Figure 14**). "**Discoveries**" is a valuable, quick introduction to IMAGE's accomplishments since 2000.

The impact of POETRY's various products is indicated by a tabulation of their content and the size of the audience reached since IMAGE/POETRY was initiated in 1997 **(Table 7)**.

Several POETRY products have had independent evaluations and have won many awards. The "Blackout!" video won Crystal Awards in The Communicator Video Competition in 1999 in the categories of Education and Special Effects/Animation. "Blackout!" also won two Telly Awards. The POETRY web site was selected for the Study Web Academic Excellence Award and Cyber-Teddy's Top 500 Web Site Award. The Soda Bottle Magnetometer Activity was selected as a high-quality resource by the National Science Teachers Association (NSTA) as part of their SciLinks program. Many POETRY products have been reviewed and approved for inclusion in the Space Science Education Resource Directory

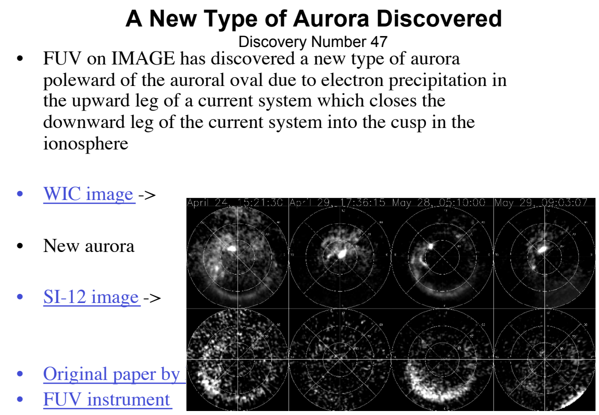

Figure 14. *One of the IMAGE* ***"Discoveries"*** *pages, which present cutting-edge IMAGE results to the public. See http://image.gsfc.nasa.gov/poetry/IMAGEdisc.html.*

http://teachspacescience.stsci.edu/cgi-bin/ssrtop.plex, such as the Space Weather CD-ROM and a number of our downloadable workbooks, including "Exploring the Earth's Magnetic Field," "Northern Lights and Solar Sprites," "Solar Storms and You," "Exploring Satellite Design," "Exploring Magnetic Storms," "Exploring the Wind from the Sun," and "Exploring Sunspots and Solar Activity Cycles." The POETRY web site has

Table 7. *The content and audience size (~ 70 million) of IMAGE products since 1997 exceed expectations.*

Product Type	Title	Teachers	Students	Public	Web Hits
Video	Blackout!	350	42,000	-	-
DVD	**Frequency** supplemental material	-	-	≈100,000	-
Web Site	Ask the Space Scientist	-	-	-	21 million
Web Site	POETRY	-	-	-	24.5 million
NASA-TV	NASA/Connect March 15, 2002	320,000	7.3 million	-	-
NASA-TV	NASA/Connect April 10, 2003	300,000	6.3 million	-	-
NASA-TV, PBS	"Live from the Aurora" 2003				
Student Activity	Soda Bottle Magnetometer	-	-	-	110,050
Curriculum	Workbooks	60,840	61,000	-	-
CDROM	"Space Weather"	40,000	50,000	10,000	-
Student Help	Science Fair Suggestions	-	-	-	39,000
Multimedia	Data movies	-	-	-	123,500
Lithograph	Space Weather	25,000	-	1000	-
VLF Receiver Kit	INSPIRE Radio Project	1,700	31,000	100	3.5 million
Museum Exhibits	Houston Museum of Natural Science, Lodestar Museum, etc.	10,000	100,000	200,000	-
Planetarium Shows	"Force 5" "Night of the Titanic"	10,000	50,000	150,000	-
Essay Contest	Alaskan Northern Lights	-	182	-	-
Workshops	Teacher Training	1,600	-	-	-
TOTALS		**770,000**	**14 million**	**4.6 million**	**49 million**

been submitted for evaluation by SciLinks as part of the 2003 OSS Education Product Review, which will be completed by September, 2003. In addition, POETRY will be evaluated by an independent evaluation group by October, 2003.

Teacher Professional Development. IMAGE/POETRY supports teachers in developing new curriculum materials each summer. Our teachers, Ms. Sue Higley, Mr. Tom Smith, Mr. Bill Pine, and Ms. Dorian Janney, each have over 10 years of experience in middle school and/or high school science and math instruction. Ms. Higley was chosen Teacher of the Year for Maryland in 2000 and is a nationally-certified master teacher in middle-school mathematics. POETRY has also participated in Rice University's "Masters of Science Teaching" degree program. The first two teachers trained in this program will graduate this spring, and four more are in progress.

Media and Public Outreach. In addition to the EPO activities of POETRY, the IMAGE project continues to be a major player in keeping Sun-Earth Connection science in the public eye through media outreach. IMAGE has had eleven press releases since launch, generating over one hundred newspaper articles (http://image.gsfc.nasa.gov/press_release/) and stories in magazines such as *Scientific American, Science News,* and *Physics News*. Last year IMAGE became the first geospace mission to hold an SSU http://www.gsfc.nasa.gov/topstory/20020509-imagessu.html. The May 9, 2002 IMAGE SSU, "Earth's Space-Storm Shield Offers Protection – at a Price," was very successful: the story was picked up by eight major newspapers and broadcast by TV stations across the country [Neal and Sissler, NASA/PAO, personal communication]. The SSU discussed new IMAGE observations during geomagnetic storms showing the formation of the ring current and ionospheric outflows in response to conditions in the solar wind. The IMAGE team is currently working on its second SSU, which will describe what IMAGE has learned about magnetic reconnection through its ground-breaking global imaging of the proton aurora. This SSU is planned to be presented at NASA Headquarters later this year. "Force 5", a planetarium show that uses IMAGE data and highlights IMAGE science, will be distributed this summer by Evans & Sutherland, a leading visual simulation technology company.

B. Future Plans

POETRY in 2004-2005. IMAGE will continue to develop innovative educational products and to partner with other NASA EPO programs, including the SECEF, IDEAS, LWS, and THEMIS programs in order to ensure the widest possible distribution of its products. We will continue to add to the "Discoveries" web pages and will annually revise the "Space Weather" CD, by improving and expanding its content, and manage its reproduction and distribution. We will support one or two teacher interns per year at Rice University and during the summers at GSFC.

A particular focus of POETRY activities during the next two years will be the development of additional Internet resources suitable for the NSTA SciLinks program. SciLinks is a program, supported by a grant from NASA and by fees from textbook publishers, that identifies and evaluates supplementary material for K-12 science textbooks and provides links to it over the World Wide Web. (The supplementary resources are identified by topics and SciLink code numbers in the margins of textbooks.) By participating in this growing program, IMAGE ensures that its valuable insights into aurora and space science will be available to hundreds of thousands of teachers across the country. Currently, POETRY has a single SciLink page at the web site that features our "Soda Bottle Magnetometer," which has been used by thousands of teachers since 1997. In 2004, we will increase the number of SciLinks pages to five, by including resource pages on the aurora, ring current, trapped particles, plasmasphere, and magnetosphere.

POETRY will develop the new resources that will be available through SciLinks in partnership with the Living With a Star research program. POETRY will also collaborate with LWS to allow students to explore the physical conditions in the space environment for any specific day and time or space weather condition. Suitable explanatory documents and a "Space Tour" will be developed, along with a summary archive of all of the major storm events for Cycle 23 and their geospace effects.

The NASA IDEAS program has funded a proposal by Maryland teacher Susan Higley and POETRY lead Sten Odenwald to partner with 10 schools in Maryland and Alaska to study the northern lights and the Venus Transit. This project will cover science, math, social studies, history, English, and arts in a truly multi-curricular style of exploration. The tenure of this grant is 2003-2005, and will include extensive joint studies by Alaskan and Maryland students of auroral activity and science. IMAGE will provide satellite information about the aurora, and supply the teachers and students with our education products and activities. The expected impact for this intense study is 8,000 students, with the expectation that this program will be incorporated into the curriculum of these schools beyond 2005. Once we have established this program, and optimized it, we will work to expand it so that it is adopted by the Montgomery County, Cecil County School Districts, and Alaska/Fairbanks school districts. At these levels, the student impact will exceed 100,000 and we will be able to take the next step to explore state-wide and national adoption.

IMAGE/POETRY will participate in the EPO component of the THEMIS mission, a MIDEX mission to study substorms with a constellation of spacecraft (scheduled launch: 2005). As part of the THEMIS investigation, geomagnetic data will be collected at 10 ground-based magnetic observatory stations operated by selected high schools in Illinois, North Dakota, Wisconsin, and Minnesota. POETRY will help develop explanatory documents that show how these data can be used by teachers to support existing course studies of magnetism and the geospace environment. POETRY resources such as the "Soda Bottle Magnetometer" will be used as a springboard to learning about high-precision geomagnetic investigations. Resources developed by POETRY for THEMIS will also connect the THEMIS substorm investigations with real-time IMAGE data for specific substorm events, so that students can understand the coupling between particles-and-field phenomenology from actual case studies.

POETRY will develop a new product for SECEF's Sun-Earth Day 2004 that will discuss long-term changes in the geomagnetic field (e.g., polar wander, magnetic reversals) and explore the possible consequences of such changes for the magnetosphere and geospace environment. POETRY will also broaden the scope of the IMAGE data to encompass a comparative planetology theme, linking IMAGE results to the exploration of planetary magnetospheres (e.g., ENA imaging of Saturn's inner magnetosphere following the arrival of Cassini at Saturn in July 2004) and core dynamo activity. An additional POETRY activity during this period will be to support the development of planetarium shows, including "Earth's Wild Ride," which is set on the Moon. IMAGE imagery will be used to show how the "invisible Earth" would appear to an observer on the Moon if seen using the IMAGE instruments.

POETRY in 2006-2007. During 2006-2007, POETRY will develop a "Best of IMAGE" web resource that summarizes the accomplishments of IMAGE and connect these accomplishments with specific resources that either already exist (SciLinks) or will be developed at that time. We will continue to create full-dome planetarium show segments that can be used in many productions and to revise and distribute the Space Weather CD. The POETRY website will undergo continuous improvement. The site will include an interface to CDAWEB so that IMAGE data can be retrieved for science fair or classroom research activities. An independent assessment of this resource will be undertaken to verify its suitability for the K12 community. The results of this assessment will be used in the improvement of the website.

Although some of what POETRY has accomplished in 1996-2003 was foreseen in the initial IMAGE EPO plan, many significant opportunities arose that were not foreseen, most notably the partnering with SECEF, the successful NASA/CONNECT TV programs in 2002 and 2003, the Event-Based Science "Blackout!" product, the NSTA SciLinks program, and the central role that POETRY played in suggesting the Venus Transit 2004 SECEF theme and the opportunity to discuss IMAGE in the context of long-term geospace changes. We fully expect that the years 2006 and 2007 will present IMAGE/POETRY with further "unexpected" opportunities to contribute in innovative ways to the education and public outreach goals of the Office of Space Science.

ATTACHMENT A

BUDGET SUMMARY

ATTACHMENT B
ACRONYMS

ACRONYMS

ARGOS – Advanced Research and Global Observation Satellite
AST – Autonomous Star Tracker
CDAWeb – Coordinated Data Analysis Web
CDF – Common Data Format
CIDP – Central Instrument Data Processor
C/NOFS – The Communication/Navigation Outage Forecasting System
CME – Coronal-Mass Ejection
CRL – Communication Research Laboratory
DSN – Deep Space Network
ENA – Energetic Neutral Atoms
EUV – Extreme Ultraviolet Imager
FITS – Flexible Image Transfer System
FUV – Far Ultraviolet Imager
GEO – Geocoronal Imager
GMDT – Geospace Mission Definition Team
GPS – Global Positioning System
GSRI – Geospace System Response Imager
GUVI – Global Ultraviolet Imager
HENA – High-Energy Neutral Atom Imager
HIGO – Heliospheric Imager and Galactic Observer
HVPS – High-Voltage Power Supply
IDEAS - The Initiative to Develop Education through Astronomy and Space Science
IMAGE – Imager for Magnetopause-to-Aurora Global Exploration
IMF – Interplanetary Magnetic Field
ISNA – Interstellar Neutral Atom
ISS – IMAGE software suite
LENA – Low-Energy Neutral Atom Imager
LWS – Living with a Star
MCP – Microchannel Plate
MENA – Medium-Energy Neutral Atom Imager
MIME – MENA image making engine
MMM – Mass Memory Module
MOU – Memorandum Of Understanding
NSSDC – National Space Science Data Center
NSTA – National Science Teachers Association
POETRY – Public Outreach Education, Teaching and Reaching Youth
RHESSI - Reuven Ramaty High Energy Solar Spectroscopic Imager
RPI – Radio Plasma Imager
SCU – System Control Unit
SED – Storm-Enhanced Density
SEC – Space Environment Center
SECEF – Sun-Earth Connection Education Forum
SI – Spectrographic Imager
SMI – Stereo Magnetospheric Imager
SMOC – Science and Mission Operations Center
SOC – State Of Charge
SSU – Space Science Update
TAS – Time-Attitude Synchronization Software

TEC – Total Electron Content
THEMIS – Thermal Emission Imaging System
TIMED – Thermosphere Ionosphere Mesosphere Energetics Dynamics
TWINS – Two Wide-angle Imaging Neutral Spectrometers
UCB – University of California, Berkeley
UDF – Universal Data Format
WIC – Wide-band Imaging Camera