Initial Results from the IMAGE Extreme Ultraviolet Imager

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Abstract. The Extreme Ultraviolet Imager (EUV) of the IMAGE mission is providing the first global images of the He^+ distribution in Earth's plasmasphere. The EUV instrument images the He^+ resonance line emission at 30.4 nm at a time resolution of 10 minutes and a spatial resolution of 0.1 R_E. Each image encompasses the entire plasmasphere in a single frame, to permit study of the structure and dynamics of the plasmasphere in its entirety. Here we survey several of the most striking features of the plasmasphere as seen by EUV. These features include convection tails, depleted regions that we call "voids," isolated magnetic flux tubes filled to higher He^+ density than their neighbors, and "shoulders" in the He^+ distribution.

Introduction

After more than four decades of study by ground-based and *in situ* techniques, many aspects of the plasmasphere are rather well characterized [*Lemaire and Gringauz*, 1998]. Plasmasphere research has been based on observations of whistlers [*Carpenter*, 1970], direct measurements of ions and electrons [*Gallagher et al.*, 1995], plasma wave experiments [*Carpenter*, 1992], and remote sensing by optical means [*Weller and Meier*, 1974; *Swift et al.*, 1989]. Recently Nakamura *et al.* [2000] have reported two partial images of the He^+ distribution in the plasmasphere at low spatial and temporal resolution obtained by a scanning photometer on the Planet-B spacecraft. However, we have lacked an important key to our understanding of the structure and dynamics of this region: regular global images that encompass the entire plasmasphere, at high resolution in both space and time. A number of workers have argued the effectiveness of this kind of information [*Williams et al.*, 1992], but until now it has been beyond our grasp.

Here we report initial results from the Extreme Ultraviolet Imager (EUV) of the IMAGE Mission. The EUV records the spatial distribution of He^+ in the plasmasphere at a spatial resolution of 0.1 R_E or better and a time resolution of 10 minutes. Each EUV image encompasses the entire plasmasphere in a single frame. These first global images of Earth's plasmasphere reveal a host of distinct features and behaviors, some expected but many new. Even in the case of previously-known features, global imaging offers new perspectives and opportunities for understanding. This paper surveys the wide range of plasmaspheric features and behaviors that are accessible through the EUV observations.

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The Observations

The IMAGE EUV instrument is a set of three wide-field (30°) cameras [*Sandel et al.*, 2000] that are tuned for the 30.4-nm resonance line of He^+. The three fields overlap slightly to form a fan-shaped instantaneous field of dimensions 84°×30°. Over the course of a single spin, the EUV field sweeps an 84°×360° swath across the sky and records the brightness over the entire region in pixels of 0.6°×0.6°. We join the images from the three heads in ground processing to form a complete map. At present, the flat-fielding at the edges of the fields is imperfect, sometimes leading to narrow dark bands at the two junctures. The 30.4-nm emission from the plasmasphere is optically thin, so the measured brightness is directly proportional to the He^+ column density along the line of sight through the plasmasphere.

These images are displayed in a consistent format. With one exception (Figure 4), they are from high northern latitudes, so the EUV line of sight is roughly perpendicular to the equatorial plane. The spin axis is to the left, and the spin is from top to bottom. As Earth and IMAGE move it their orbits, the apparent position of the Sun moves in the frame. A light circle near the edge of each image marks approximately the direction of the Sun. All images are scaled logarithmically, but they are displayed with different stretches, which are chosen to best illustrate their main features.

Convection Tails

Plasmasphere convection tails have been discussed in the literature for some time [*Grebowsky*, 1970; *Chen et al.*, 1975; *Carpenter et al.*, 1992]. In the accepted picture, global convection [*Nishida*, 1966] leads to a tail or plume of eroding plasmaspheric plasma that extends sunward. Unfortunately, this over simplification has obscured important, poorly understood processes in the inner magnetosphere [*Carpenter*, 1995]. Recent studies [*Elphic et al.*, 1996] used *in situ* observations to explore the complex storm-time pattern of plasmaspheric plasma at geosynchronous orbit, which is thought to involve the interaction of penetrating electric fields, dayside magnetospheric compression, and the pattern of plasmaspheric erosion. Models of convection driven dynamics [*Lambour et al.*, 1997] using the convection electric field derived from the Rice Magnetosphere Specification and Forecast Model (MSFM) [*Freeman et al.*, 1994] have accounted for the observed distribution of plasma measured by the Los Alamos Magnetospheric Plasma Analyzers (MPA) on three geosynchronous satellites [*McComas et al.*, 1993].

Many of the details of thermal plasma distribution remain unexplained, owing largely to the difficulty of charac-

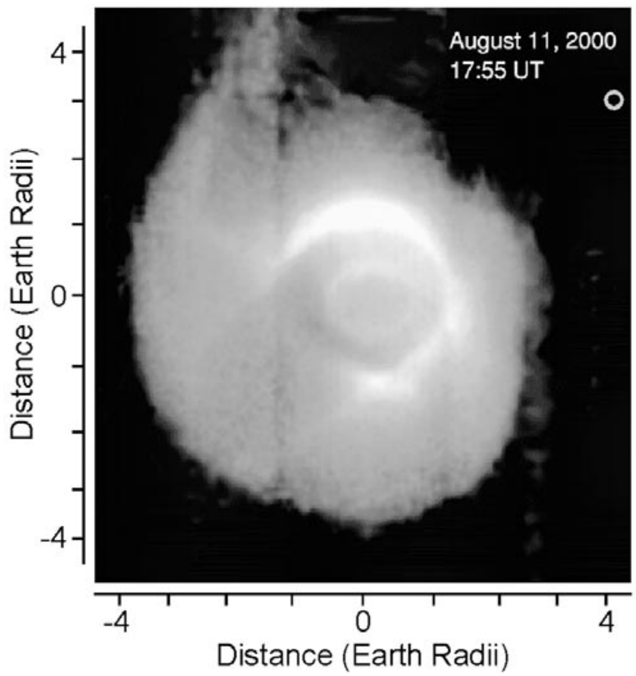

Figure 1. He^+ distributions on 11 August 2000. The small circle to the upper right marks approximately the direction toward the Sun, and Earth's shadow is the dark region extending through the plasmasphere toward the lower left. A plasma tail extends sunward from the main plasmasphere near the dusk meridian.

terizing the plasmasphere by *in situ* measurements. Combining global EUV observations and *in situ* measurements, such as by the Los Alamos geosynchronous MPA, permits a much more robust analysis of plasmaspheric processes than possible earlier.

As seen by EUV, the convection tails consist of narrow regions of enhanced density that are connected to the main body of the plasmasphere in the dusk sector and extend sunward (Fig. 1). Typical size scales are 3–5 R_E in length and 0.5–1.0 R_E in width, and the contrast over the gap that separates the tail from the main plasmasphere is typically a factor of 6 in brightness. We have identified ten instances of tails (some less distinct than in Fig. 1) in the EUV data for the period of 20 May to 31 August 2000. In each case, the tail formed during or within a few hours after a period of K_p at least 5.

Fig. 2 shows our most spectacular example of a tail-like structure. It may be inappropriate to classify this structure with the tails described above, because it appears to differ in qualitative ways from most of them. The most striking difference is the nearly-perpendicular juncture with the main plasmasphere. The other tails observed by EUV join the main plasmasphere nearly tangentially. This feature also exhibits more internal structure than usual tails, but this may simply reflect its larger size. The structure is not simply a single flux tube, because the viewpoint lies nearly in the meridian plane of field lines through the feature. The width of this tail is ~ 1 R_E and its length is at least 3 R_E.

Plasma Voids

We have identified two types of roughly radial density structure, the first dimmer than the surrounding plasmasphere and the second brighter. They differ in size in both the radial and azimuthal directions. It is possible that later observations may show these two phenomena to be part of a continuum that extends between the examples that we have in hand. However, for the reasons that we describe below, we believe that the structures arise from different physical processes.

The first of the two structures we call a void (Fig. 3). They are large and long-lived. In the example in Fig. 3, the region of lower density extends radially outward from $L \sim 2.5$ to the plasmapause (as defined by the major portion of the plasmasphere) at $L \sim 4$. The azimuthal extent is $\sim 20°$. The contrast against the main plasmasphere, measuring in azimuth at a radial distance near the center of the feature, is a factor of ~ 3 in brightness. Seen here ~ 3 hours after its first appearance in the EUV images, it persisted for the following 38 hours with much the same shape. During this time it co-rotated with the magnetic field. Because of the unfavorable viewing perspective at the time, the details of the process that filled the void are unclear.

On 1 July, EUV recorded a second void, again of similar size. The shape was similar also, including the small (~ 0.4 R_E) peak in the center. It corotated and persisted for ~ 48 hours. The first void appeared after a period of high magnetic activity ($K_p \sim 5$) but the second void formed after several days of $K_p \leq 3$ conditions. The longevity of these voids is generally consistent with estimates of the time scale for refilling depleted flux tubes from the ionosphere [*Gallagher et al.*, 1995].

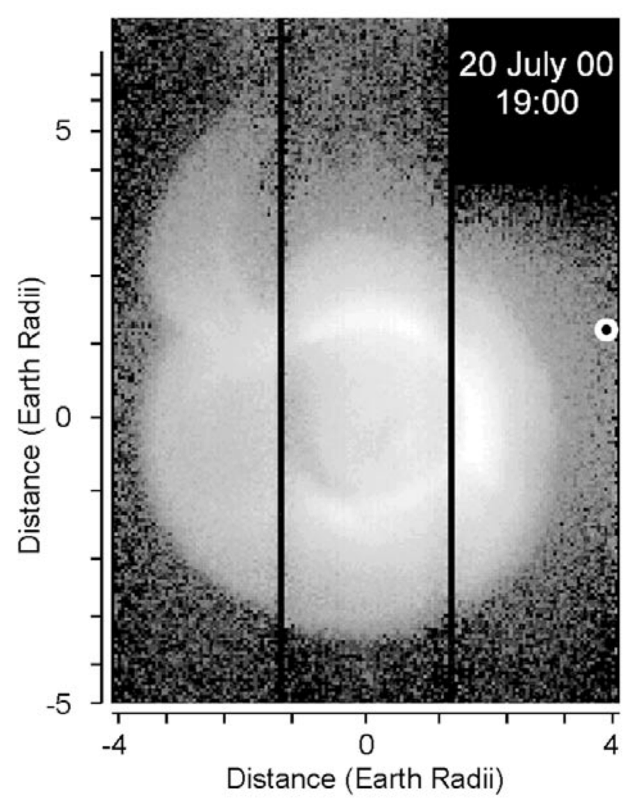

Figure 2. The most spectacular example of a convection tail recorded to date. The latitude of IMAGE was about 83 N, so the plane of the figure nearly coincides with the equatorial plane.

Enhanced Flux Tube Content

The second of the two density structures appears in the images as features that we call here "fingers." They are regions of enhanced brightness having radial extents of 1–2 R_E and azimuthal extents of up to 20°. One plausible interpretation is that these structures represent isolated flux tubes that have been filled to higher densities than neighboring tubes. When viewed from a position at high magnetic latitude, such flux tubes would appear projected into the plane of the magnetic equator, leading to the observed finger-like appearance.

Support for this interpretation comes from images acquired on 20 August 2000. Figure 4 is one of a series of images showing an isolated flux tube that is substantially brighter than its neighbors. Because of the viewing perspective (from above a magnetic latitude of 53°), we can see that the brightness enhancement follows the curve of the magnetic field lines. The earlier and later images show the flux tube appearing out of Earth's shadow, and then rotating through ∼ 40° before EUV observations terminated for that orbit. At still earlier times, before the flux tube entered the shadow, the viewing perspective was from high latitudes, and the enhanced brightness appears as a finger. The same feature is visible in images from the succeeding orbit as well, so the enhancement in flux-tube content persisted for at least 12 hours. This feature first became apparent in the EUV images after several days of magnetically quiet conditions.

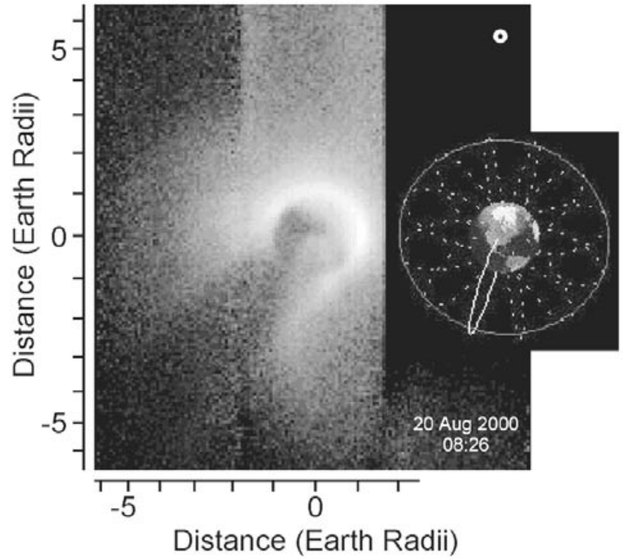

Figure 4. The bright region extending downward from the center of Earth is probably an isolated flux tube that has a higher He^+ content that its neighbors. This view is from a magnetic latitude of 53°. This same region appears as a "finger" when viewed from higher latitudes. In the illustration of the geometry at the right, the faint solid curve is a circle of radius 3 R_E in the magnetic equatorial plane. The dashed curves and the bright white curve are dipole field lines at $L = 3$.

Other Features

A structure in the He^+ distribution called a "shoulder" [*Burch et al.*, 2001a, b] is of particular interest. Shoulders are characterized by a sharp azimuthal gradient in He^+ density toward earlier local times. *Burch et al.* [2001b] discuss these shoulders in more detail and suggest that their origin may be related to a rapid increase in solar wind density and a transition to southward IMF B_z. The EUV was not designed for the study of auroras, but some auroral emission falls within its passband. Although a portion of this light may be at EUV's target wavelength of 30.4 nm, it seems likely that much of it is at longer wavelengths, such as the O^+ line at 53.9 nm [*Burch et al.*, 2001a].

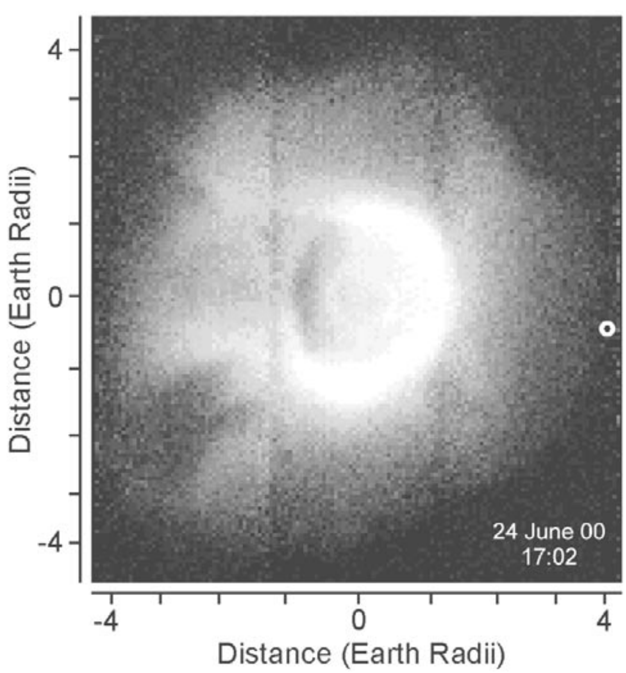

Figure 3. The dark region to the lower left of Earth is an example of a void, a region of reduced plasmaspheric density. This void corotated with the magnetic field and persisted for ∼ 38 hours.

Conclusions

These images emphasize the effectiveness of plasma imaging techniques for studies of structure and dynamics of plasmas. Questions of how thermal plasmas are distributed in the inner magnetosphere no longer need be at the forefront of our thinking. Our efforts now shift to the central questions of why thermal plasma behaves as it does. How do storm convection electric fields penetrate into the body of plasmasphere [*Elphic et al.*, 1996]? What are the dominant mechanisms and consequences of interactions between the plasmasphere, ring current, and superthermal electron populations [*Fok et al.*, 1995; *Khazanov et al.*, 1997]? During storms, how much plasmaspheric plasma is lost into the ionosphere and how much is eroded by sunward convection [*Park and Carpenter*, 1970]? How does recovery and flux tube refilling proceed [*Lemaire and Gringauz*, 1998]? What are the mechanisms that produce the small-to-large-scale features observed in the spatial distribution of He^+ plasma? These questions highlight the new challenges and opportunities brought to us by IMAGE remote sensing of the inner magnetosphere with the EUV.

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