Electric fields deduced from plasmapause motion in IMAGE EUV images

J. Goldstein,1,2 R. A. Wolf,1 B. R. Sandel,3 and P. H. Reiff1

Received 8 October 2003; revised 25 November 2003; accepted 30 November 2003; published 2 January 2004.

[1] The IMAGE extreme ultraviolet (EUV) imager obtained global images of the plasmasphere erosion of 10 July 2000, in which the nightside plasmapause moved inward by about 2 RE during 5–8 UT. We use plasmapause motion to infer the electric (E) field component tangent to the moving plasmapause; in general we lack knowledge of the perpendicular E-field component. In the midnight-to-dawn quadrant where the plasmapause shape is very nearly circular, the tangential E-field component is equal to the azimuthal electric field $E_{\phi}$. Peak westward E-fields of 0.6–1.3 mV/m were found at the plasmapause between $L \approx 4–6$, an inner magnetospheric E-field that was 25% of the solar wind E-field. The MLT-concentration of the inferred E-field suggests that convective flows may produce partial indentation of the nightside plasmapause (especially in the midnight-to-dawn sector) that widens as the edges of the indentation propagate azimuthally.

INDEX TERMS: 2712 Magnetospheric Physics: Electric fields (2411); 2730 Magnetospheric Physics: Magnetosphere—inner; 2768 Magnetospheric Physics: Plasmasphere.


1. Introduction

[2] The traditional picture of the shrinkage of the plasmapause during an active period holds that the boundary simply $E \times B$-drifts in the time-varying large-scale convection electric (E) field; this view has been represented computationally by various authors (e.g., Grebowsky [1970] and Spiro et al. [1981]). It has also been suggested that instabilities or other more complicated processes might play an active role [Carpenter and Lemaire, 1997]. The extreme ultraviolet (EUV) imager on the IMAGE satellite [Sandel et al., 2001] has provided previously unavailable global images of the plasmasphere with spatial and temporal resolutions of 0.1 RE and 10 minutes. These global observations of plasmapause shape and dynamics may help determine whether the simple picture from the 1960s and 1970s is correct, or whether more subtle physics is involved. IMAGE EUV has already confirmed the existence of plasmaspheric drainage plumes, a prediction of the early models [Grebowsky, 1970; Sandel et al., 2001].

[3] Carpenter et al. [1972] used the motion of whistler ducts during substorms to infer the equatorial distribution of the azimuthal component of the convection E-field. Burch et al. [2001] suggested a similar approach using EUV observations of the time-dependent plasmapause. Goldstein et al. [2003a] reported the first observation by IMAGE EUV of a nightside plasmaspheric erosion event on 10 July 2000, and other similar events have since been studied [Spasojević et al., 2003; Goldstein et al., 2003b, in press]. In this letter we demonstrate that it is indeed possible to infer electric fields from plasmapause motion captured by EUV during erosion events. We apply our technique to the 10 July 2000 plasmasphere erosion.

2. EUV Plasmapause Extraction

[4] IMAGE EUV obtains global images of the plasmasphere by detecting 30.4-nm sunlight resonantly scattered by the He$^+$ ion population. In the EUV image of Figure 1a, the brightness of each pixel is proportional to the line-of-sight integrated He$^+$ column abundance (in cm$^{-2}$). The image has been mapped to the magnetic equator by assigning to each pixel the minimum dipole $L$-shell along its line of sight [Roelof and Skinner, 2000]. The plasmasphere is the green-white region surrounding the Earth out to radial distances of roughly 4–5 RE on the nightside. A slight drop in intensity behind the Earth is caused by the Earth’s shadow (‘S’ in Figure 1a). The nightside plasmapause in Figure 1a is identifiable as the sharp transition from green to speckled black color [Goldstein et al., 2003c].

[5] We extracted plasmapause locations from thirty-three EUV snapshots between 4:03–9:30 UT on 10 July 2000. Figure 1 illustrates the plasmapause extraction technique using the 7:07 EUV image. Points along the plasmapause were manually selected (by clicking on an EUV image with a computer mouse) with an average azimuthal spacing of 1 hour of magnetic local time (MLT). In Figure 1a these manually-selected (‘click’) points are overplotted on the EUV image as filled white circles. On much of the dayside no plasmapause was identifiable. For each EUV snapshot, an array of click points $(r, \varphi)$ was obtained, where $r = LR_E$ and $\varphi = \pi(MLT - 12)/12$.

[6] Each array of click points was interpolated by Fourier series expansion

$$R_{pp}(\varphi) = R_E \sum_{k=0}^{K} \left[ C_k \cos(k\varphi) + S_k \sin(k\varphi) \right] (1)$$

where $C_k$ and $S_k$ are standard Fourier series coefficients except for the conventional zeroth terms which have been absorbed inside the summation in our expression. (Note $S_0 = 0$.) We limited the number of terms $K$ in each
Figure 1. Example of extraction of plasmapause curve from IMAGE EUV, 10 July 2000, 7:07 UT. (a) EUV image, mapped to the magnetic equator (Earth at center; Sun to the right). Dotted lines are X- and Y-axes; dotted circle is geosynchronous orbit. The colorbar gives line-of-sight integrated He+ column abundance. Black region in upper right is sunlight contamination. Filled white circles are manually-extracted ('click') points along the plasmapause. (b) Fourier expansion of the click points (circles) is plotted as the solid curve.

expansion according to the average azimuthal spacing $\Delta \varphi$ of each click point array: $K = \pi/\Delta \varphi$. $K$ ranged from 10–15 for the 33 Fourier expansions. In Figure 1b the click points (circles) and their Fourier expansion with $K = 13$ (solid curve) are plotted. The Fourier curve agrees with the 7:07 EUV plasmapause to within one or two pixels (0.1–0.2 $R_E$). Fourier interpolation allows each plasmapause curve to be represented analytically. The use of analytical expressions not only permits easy specification of the plasmapause radius at arbitrary $\varphi$, but also significantly simplifies the analysis (and reduces the computation) necessary to infer E-fields from the plasmapause motion. All of the time dependence of the 33 plasmapause curves of 10 July 2000 is contained in the Fourier coefficients $C_k$ and $S_k$.

3. Electric Field From EUV Images

[7] The motion of the plasmapause boundary in a sequence of EUV images can be related to an equatorial electric field as follows. We assume that the boundary $R_{pp}(\varphi, t)$ is comprised of a large number cold plasma parcels subject only to $E \times B$ drift at the magnetic equator, and that these parcels will always collectively define the equatorial plasmapause, regardless of their motion. (Note: plasmapause $\neq$ Alfvén layer.) The $E \times B$ assumption includes the possibility of both contraction (i.e., compression) and erosion (i.e., removal) of the plasmapause plasma. In electric field $E = E_r \hat{r} + E_\varphi \hat{\varphi}$, cold plasma in magnetic field $B = B_r \hat{r} \times \hat{\varphi}$ will $E \times B$-drift both radially and azimuthally according to the equations of motion $\dot{r} = E_r/B$ and $\dot{\varphi} = -E_\varphi/(rB)$. If the detailed motions of the plasma parcels along the boundary $R_{pp}(\varphi, t)$ are known, then the vector E-field at that boundary is completely specified. The radial drift speed at the boundary is

$$\dot{r} = R_{pp}(\varphi, t) = \left( \frac{\partial R_{pp}}{\partial \varphi} \right) \varphi + \left( \frac{\partial R_{pp}}{\partial t} \right) ,$$

(2)

where subscripts $t$ or $\varphi$ are held constant for partial derivatives. It is clear that $\left(\partial R_{pp}/\partial \varphi\right)_t \equiv V_{pp}$ is the radial speed of the plasmapause at a single MLT value, and $\left(\partial R_{pp}/\partial \varphi\right)_t$ describes the azimuthal variation of $R_{pp}$ from a single EUV snapshot; both these quantities can be determined easily from (1) and arrays $C_k$ and $S_k$. Inserting the equations of motion for $\dot{r}$ and $\dot{\varphi}$, and $V_{pp} = (\partial R_{pp}/\partial \varphi)_t$, into (2) gives

$$E_\varphi + \frac{E_r}{R_{pp}^2} \left( \frac{\partial R_{pp}}{\partial \varphi} \right)_t = V_{pp} B.$$  
(3)

Defining the unit vector $\hat{n}$ tangent to the plasmapause $R_{pp}$ as

$$\hat{n} = \left[ \hat{\varphi} + \frac{1}{R_{pp}} \left( \frac{\partial R_{pp}}{\partial \varphi} \right)_t \right] \cos \alpha$$

(4)

with

$$\cos \alpha \equiv \left[ 1 + \frac{1}{R_{pp}^2} \left( \frac{\partial R_{pp}}{\partial \varphi} \right)_t^2 \right]^{-\frac{1}{2}}$$

(5)

allows (3) to be written

$$(E \cdot \hat{n}) \equiv E_\varphi = V_{pp} B \cos \alpha.$$  
(6)

Thus a time-series of EUV-derived plasmapause curves does not provide a complete description of the electric field, but rather only the component ($E_\varphi$) tangent to the moving plasmapause boundary. This is because it is difficult to estimate motion along the relatively smooth/featureless $R_{pp}$ curves (such as plotted in Figure 1) that are typically observed by EUV on the nightside during erosions. Using (6) and assuming dipole B we determined the tangential E-field component $E_\varphi$ for the 33 EUV plasmapause curves between 4:03–9:30 UT. The time derivatives of the Fourier coefficients $C_k$ and $S_k$ required to obtain $V_{pp} = (\partial R_{pp}/\partial \varphi)_t$ from (1), were calculated by centered finite difference. The $\varphi$-derivatives were calculated analytically.

[8] As reported by Goldstein et al. [2003a], the 10 July erosion caused the nightside plasmapause to move about 2 $R_E$ inward during 5–8 UT. Most of the 10 July erosion was concentrated into two bursts of inward plasmapause motion during 5–6 UT (‘I’) and 6:40–8 UT (‘II’); these bursts can be correlated with southward IMF transitions [Goldstein et al., 2003a]. The most pronounced erosion in bursts (I) and (II) occurred at 5:25 and 7:07 UT respectively.
Figure 3. Electric field inferred from IMAGE EUV, 10 July 2000. (a) $E_\pi$ (E-field tangent to the moving plasmapause boundary) versus UT and MLT. Colorbar gives strength in mV/m, saturated at $-0.9$ mV/m. (White = no data.) (b) $E_\theta$ (azimuthal E-field) estimated from $E_\pi$ for cases in which $\alpha \leq 8^\circ$, where $\cos \alpha \equiv (\hat{\pi} \cdot \hat{\varphi})$.

Figure 2 depicts our $E_\pi$ determination at these two selected times. In 2(a) $E_\pi$ vectors are drawn with their tails at the locations where they were obtained, and scaled as $1 R_\oplus = 0.8$ mV/m; vectors are only drawn at a few $\varphi$ values to avoid cluttering up the plot. Another way to represent this data is shown in 2(b), which plots $E_\pi$ vectors rotated 90° so that they point in the direction of the associated flows. We note that negative $E_\pi$ points westward, and corresponds to radially inward plasmapause motion. From Figure 2, the peak $E_\pi$ magnitude was about 1.3 mV/m and occurred during the second erosion burst (II). In burst (I), the peak $|E_\pi| = 0.6$ mV/m was about half that of (II). From whistler duct motion, Carpenter et al. [1972] deduced westward E-fields of strength 0.5–0.6 mV/m, comparable to (I) but weaker than (II). We also note that our E-field strength is approximately 25% of the 10 July 2000 solar wind E-field reported by Goldstein et al. [2003a].

Figure 3a shows inferred $E_\pi$ values from the entire 10 July erosion event, plotted as intensity (color) versus UT and MLT. White (no color) means no $E_\pi$ value was obtained (because no plasmapause was identifiable). The two main bursts (I) and (II) of erosion ($E_\pi < 0$) show up in 3(a) as horizontal bars of red/yellow (westward $|E_\pi| > 0.4$ mV/m). As mentioned above, $E_\pi$ in burst (II) was stronger than burst (I). The MLT dependence of westward $E_\pi$ will now be discussed, keeping in mind that ‘westward’ means $E_\pi < 0$. In (I), $E_\pi$ is 1.3 to 1.5 times stronger within 0–7 MLT than at pre-midnight local times, and varies by only 10 percent within 0–7 MLT. Post-dawn $E_\pi$ strength drops precipitously with increasing MLT, from (6 MLT, $-0.6$ mV/m) to (8 MLT, $-0.25$ mV/m). Post-midnight concentration of westward $E_\pi$ is consistent with the local-time dependence of penetration E-field noted by Carpenter et al. [1972] and seen in Jicamarca radar data [Fejer and Scherliess, 1995]. By ‘penetration E-field’ we mean the part of the convection E-field that penetrates the inner magnetospheric shielding layer [Goldstein et al., 2003a]. The second burst (II) is separated into two intervals with different MLT dependences. In (IIA) $E_\pi$ below $-0.6$ mV/m is found all across the nightside, between 20–07 MLT (varying by 30 percent within that MLT range), with the strongest westward $E_\pi$ near midnight. As noted by Goldstein et al. [2003a], the second 10 July erosion burst (II) may have been intensified by a global magnetospheric compression that created a strong inductive E-field, which is consistent with the MLT dependence of (IIA). We note, however, that there was also a strong solar wind E-field (~5 mV/m) correlated with the second burst of erosion, so it is likely that both penetration and inductive E-fields contributed. Just before 8 UT, (IIB) shows similar MLT dependence to (I), so that (IIB) may also be interpreted as penetration E-field.

[10] From equation (4), $\cos \alpha \equiv (\hat{\pi} \cdot \hat{\varphi})$; i.e., if the plasmapause is perfectly circular, $\cos \alpha = 1$ and (6) reduces to $E_\pi = V_{ppB}$, a purely azimuthal E-field. In general, however, $E_\pi$ will contain contributions from both $E_r$ and $E_\theta$. To express $E_\pi$ in terms of $\hat{\pi}$ and $\hat{\varphi}$ (more useful than the time-varying non-standard unit vector $\hat{\pi}_r$), we could: (A) estimate $\hat{\pi}$ and use this estimate to compute $E_r$ and $E_\theta$ from $E_\pi$; (B) apply the technique only for ‘nearly circular’ $R_{pp}$ curves, thus obtaining an estimate for $E_r$. In approach (A), $\hat{\pi}$ could be estimated using modeling and/or additional measurements, but such (extensive) additional effort is beyond the scope of this letter, in which we seek merely to demonstrate what information can be extracted from EUV data alone. We therefore chose approach (B). In Figure 3b, $E_\pi$ values for which $\alpha > 8^\circ$ have been removed (set to white). The remaining data have $\alpha \leq 8^\circ$, corresponding to $\cos \alpha \geq 0.99$. In other words, plotted in 3(b) is the subset of $E_\pi$ data for which the plasmapause is very nearly circular; i.e., $(\hat{\pi} \cdot \hat{\varphi}) \approx 1$, and $E_\pi \approx E_r$. In Figure 3b a good estimate for $E_r$ is thus obtained for the post-midnight (0–6 MLT) sector, and portions of pre-midnight at scattered times.

[11] We now discuss the regions of non-circularity, and what they imply for erosion dynamics. During the initial phase of the 10 July erosion, a broad plume of sunward-moving dayside plasma forms. As a result, the plasmapause is noncircular at the dawn and dusk flanks. Plasmapause non-circularity is also related to the MLT dependence of $E_\pi$ discussed above. During the erosion, strong $E_\pi$ (i.e., strong radial flow) is concentrated in some MLT range $\Delta M$ (0–7 MLT for (I) and (IIB); 20–07 MLT for (IIA)) and is also roughly constant (to 10–30%) within $\Delta M$. The plasmapause radius within $\Delta M$ is smaller than in surrounding areas and roughly circular, but at the edges of the sector $\Delta M$ the plasmapause bulges outward. These ‘edge bulges’ or ‘ripples’ then propagate azimuthally. Such an erosion scenario, involving partial indentation of the nightside plasmapause, was proposed by Carpenter and Lemaire [1997], and is supported by our results. In Figure 3a a broad diagonal band (‘D’) of red/yellow extends from
Additional information other than that provided by EUV can be inferred only the component of electric field tangent to the plasmapause boundary. In the case that the plasmapause is roughly circular, the inferred tangential E-field component is approximately equal to the azimuthal electric field $E_\phi$.

[14] Analysis of $E_\phi$ in particular events can shed light on some of the details of the erosion process. For the 10 July 2000 erosion event, we found peak westward E-field strengths of 0.6–1.3 mV/m at plasmapauses between $L = 4$ and $L = 6$, an inner magnetospheric E-field magnitude that was 25% of the solar wind E-field. At some times during the erosion $E_\phi$ was concentrated mostly in post-midnight MLTs, consistent with a penetration E-field interpretation and with the results of Carpenter et al. [1972]; Fejer and Scherliess [1995] and Carpenter and Lemaire [1997]. During one interval, a larger MLT swath of the plasmapause moved inward at the same time, perhaps due to E-fields associated with a magnetospheric compression [Goldstein et al., 2003a]. The erosion process may very well involve partial indentation of the nightside plasmapause in MLT sectors where $E_\phi$ is concentrated, as proposed by Carpenter and Lemaire [1997]. Bulges at the edges of the indentation propagate azimuthally, yielding a rough estimate of azimuthal flows. We have demonstrated how the technique of Carpenter et al. [1972] may be modified for use with EUV images to deduce $E_\phi$ information that is reasonable, but unvalidated by independent measurements. Validation is the next step in this project.

[15] Acknowledgments. We are grateful to D. Carpenter, E. Roelof, and many other members of the community, for helpful discussions during the development of this project. The IMAGE mission under NASA contract NAS5-96020 supported work at Rice and U. Arizona. Some work at Rice was supported by the NASA SEC Theory program under ATM NAG5-1181. Research at SwRI was funded by the NASA SEC Guest Investigator program under NAG5-12787.

References


4. Conclusions

[13] Recently there has been renewed interest in inner-magnetospheric and mid-latitude-ionospheric electric fields (e.g., Rowland and Wygant [1998]; Burke et al. [1998]; Foster et al. [2002]). We have demonstrated that E-fields may be inferred from global plasmapause motion observed by IMAGE EUV. We do not yet have a robust method of following the motion of individual plasma parcels along the plasmapause in EUV images. Therefore with no


J. Goldstein, Space Sci Div, Southwest Research Institute, San Antonio, TX 78228, USA. (jerru@alum.dartmouth.org)
R. A. Wolf and P. H. Reiff, Department of Physics and Astron, Rice University, Houston, TX 77005, USA.
B. R. Sandel, Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721, USA.