Origin and evolution of deep plasmaspheric notches

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Deep plasmaspheric notches can extend over more than 2 $R_E$ in radial distance and 3 hours MLT in the magnetic equatorial plane, as observed by the extreme ultraviolet (EUV) imager on the IMAGE mission. They are among the largest evacuated features in the exterior plasmaspheric boundary. They can last for days and exhibit a variety of shapes. It appears that weak convection and limited erosion precedes notch formation at the westward, near-Earth edge of the convection plume. Eighteen clear notch events were found and analyzed in 2000. Among these events, notches were found to drift as slowly as 44% of corotation. In only one case was a notch found to drift at the corotation rate within measurement error. On average, these notches drift at about 21.5 h d$^{-1}$ or 90% of the corotational rate. Notches sometimes exhibit an interior structure that appears as an extended prominence of dense plasma, which forms a W- or M-like feature in IMAGE/EUV images, depending on viewing perspective. Initial modeling suggests that notches and notch prominences may be caused in part by intense small-scale potential structures that result from the localized injection of ring current plasma. Plasma filling rates during recovery are examined in three L shell ranges from L = 2 to L = 3.5 with rates ranging from 5 to 140 cm$^{-3}$ d$^{-1}$. Plasma loss during a minor substorm is found to extend to surprisingly low L shell with rates ranging from 100 to 130 cm$^{-3}$ d$^{-1}$ across the L shells examined.


1. Introduction

The plasmasphere, a relatively dense toroidal region of cold plasma surrounding the Earth, has been studied for many years [see Lemaire and Gringauz, 1998] and is thought to play an important role in energetic particle scattering and the transport of energy in the inner magnetosphere [e.g., Fok et al., 1993; Liemohn et al., 2000; Khazanov et al., 2003]. Density structures on a variety of scale sizes have been found in plasmaspheric plasma [Carpenter et al., 2002; Sandel et al., 2003]. The outer boundary of the plasmasphere, referred to as the plasmapause or plasmaspheric boundary layer, is often characterized by an abrupt one to two orders of magnitude drop in plasma density. During extended geomagnetically quiet conditions this region may lack a sharp boundary and instead exhibit a density that gradually falls to trough levels. The most significant azimuthal plasmaspheric structure is the plume, which extends sunward in afternoon and evening local times. The dominant mechanism for plume formation is the global cross-tail electric field induced by the solar wind streaming through the Earth’s outer magnetic field [Nishida, 1966; Grebowsky, 1970]. Recently, it has become clear that the details of plume structure are also dependent on more localized electric fields [Foster et al., 2002; Goldstein et al., 2004a, 2004b; Liemohn et al., 2004].

Notches [Sandel et al., 2003] represent one of the largest density structures in the plasmasphere, along with the plasmasphere itself, the plasmaspheric plume, and plasmaspheric channels. Notches may contribute to in situ observations previously described as density cavities inside the plasmasphere [Carpenter et al., 2002]. This possibility was demonstrated by Green et al. [2002], where corotation of a plasmaspheric notch in combination with orbital satellite motion was found able to reproduce the in situ measurement properties of an interior density cavity. Notches have recently been found to play an important role in the generation of kilometric continuum radiation [Green et al., 2002, 2004], known for many years to be a pervasively observed plasma wave in the outer magnetosphere low-density cavity.

Notches are characterized by deep density depletions that extend mostly radially inward to L = 2 or less. The sizes
in local time range from very narrow (~0.1 hours MLT) to very broad (~3 hours MLT). Notch densities observed by extreme ultraviolet (EUV) are found to be a factor of 5–10 below the adjacent notch walls, although interior notch densities often fall to the EUV noise level so that notch depletions may be much deeper. Figure 1 shows three examples of plasmaspheric notches. Each panel is a 10-min integrated image acquired by the EUV camera on the IMAGE mission. The camera observes 30.4 nm sunlight resonantly scattered by He+ ions in the plasmasphere. The present work explores the origin of these deep, large density cavities in the outer plasmasphere and their evolution. Only clear, distinct notches observed during 2000 are examined here. The appearance of especially narrow (in local time) notches is more subject to viewing geometry and difficult to follow in time. Notchlike features that are broad in local time, but shallow in L shell, may be related to the notches explored here or may be related to another morphological feature referred to as crenulations. Crenulations are irregular features in plasmapause L shell whose origins are unclear, although they appear to bear similarity to shoulder features associated with overshielding and undershielding in the inner magnetosphere [Goldstein et al., 2002; Spasojević et al., 2003]. It is found that notches appear to share their origin with low-density channels, which are formed during recovery at the base of the plasmaspheric plume in the dusk region. Long-lived notches present the opportunity to follow their refilling and motion across a wide range of L shells. In one notch, refilling is found to be consistent with previous early time refilling, but responsive to a brief increase in magnetic activity. Notches are also found to routinely drift eastward at a rate below corotation [Sandel et al., 2003] and often at the same rate across a wide range of inner L shells.

2. Origin of a Notch

2.1. Observational Evidence

[7] Figure 2 shows the plasmasphere near the start of recovery from a period of enhanced convection. Each panel shows a plume in the dusk region that will soon drift eastward in the corotation direction. While otherwise similar, the first two events on 31 May 2000 and 30 June 2000 precede the formation of a notch. The third event on 10 June 2000 results in an extended low-density channel. These three event periods are shown again a short time later in Figure 3. A much more clear difference has developed in the plasma distribution between the first two (Figures 3a and 3b) and the third event (Figure 3c) as shown from left to right in Figure 3. The first two events develop into radial notch structures, while the third event forms a low-density, azimuthal channel inside a wrapped plume. Of the few notches so far observed during formation, all appear to originate at the westward edge and base of the convection plume upon recovery from enhanced storm-time convection. The entrainment and wrapping of the convection plume during storm-time recovery was first proposed by Grebowsky [1970] and subsequently discussed in many studies [see, e.g., Carpenter et al., 1992; Sandel et al., 2001; Spasojević et al., 2003]. The process results in an azimuthally extended and radially narrow region of low density inside a similarly extended region of enhanced density that was once the sunward extended plume.
From EUV observations during 2000, notches appear to originate during storm-time recovery in the same region as low-density channels. Observationally, the distinction between notch and low-density channel formation appears to be due to the size and/or plasma content of the storm-time plume and correspondingly to the degree of plasmaspheric erosion. In order to illustrate these distinctions, two periods of notch formation (Figures 2a and 2b and Figures 3a and 3b) are compared to a period of low-density channel formation (Figures 2c and 3c). The two notch

Figure 2. Storm-time recovery of the plasmaspheric plume on three different days. Two of the days on 31 May 2000 and 30 June 2000 result in the formation of a notch. The day of 10 June 2000 results in the formation of a low-density channel.
events are characterized by a thin plume and limited erosion of the plasmasphere. Much more of the outer plasmasphere was eroded in the channel event. With the aid of the cartoon presented in Figure 4, we illustrate the observed differences in notch and channel formation. In Figure 4, time proceeds from left to right with notch formation shown across the top of Figure 4 and channel formation across the bottom. The upper sequence illustrates that limited plasmaspheric erosion and smaller erosion plume leads to the formation of a plasmaspheric notch, while more extensive plasmaspheric erosion and plume are associated with the development in recovery of a long, thin plume draped across the plasmasphere forming a low-density channel.

[9] Careful examination of the events shown in Figures 1a and 3b reveal the presence of a thin wispy remnant of the convection plume overdraping the notch density cavity. While not always visible in EUV images, we hypothesize that a remnant plume often remains, at least for a short period of time after the formation of a notch. The details of electric fields and other thermal plasma drivers that control the distinction between notch and channel formation are left to subsequent analysis. It should be noted that in some cases extended low-density, channel-like structures are observed to reorient into radial low-density notches. Likewise, EUV has also observed features that were likely W-shaped notches (see below) entrained within the eastward extent of low-density channels. Also, while the residual azimuthally draped plume in notch events quickly disappears from EUV images, an observationally similar, but slower disappearance is observed in the wrapped plumes that result in low-density channels [Grebowsky, 1970; Chen and Wolf, 1972; Adrian et al., 2001].

[10] In order to more easily examine plasmaspheric features and variations in plasma content over time, subsequently shown EUV images are projected into the dipole magnetic equatorial plane and counts are transformed into pseudodensity, where modeled variations in solar irradiance at 30.4 nm and the most dominant systematic influences of image intensity across the field of view are removed. This analysis is discussed in Appendix A.

[11] A notch sometimes includes an interior azimuthally narrow radial density enhancement, or prominence. An example of such a prominence is shown in Figure 1a. In this example, the prominence is nearly as broad as the notch near the Earth and rapidly narrows in azimuth with increasing L shell such that it forms something like a “W” in enhanced density. Although not visible in this rendering of the event, prominences can sometimes be seen to extend across the entire radial length of the notch and with a very narrow azimuthal extent (~0.1 Rd).

[12] An interior prominence can be seen to form just after notch formation during the event on 24 June 2000, which is shown in Figure 5. Pseudodensity images mapped into L shell versus MLT are shown at 30 min intervals over a period of 2 hours. Only the 5-hour MLT region centered on the notch is shown in each image. In the leftmost image the notch has recently formed just westward of the recovering convection plume. The notch walls become more radial and distinct as the feature evolves leaving an enhanced prominence near the notch center. While a definitive explanation for the formation of a notch prominence is not yet available, a candidate mechanism can be suggested.

2.2. Computational Explanation

[13] A possible mechanism for the formation of a plasmaspheric notch and a prominence within a notch is intense, small-scale electric field structures in the inner magnetosphere. This is best described by considering a few numerical results. Figure 6 shows magnetic equatorial plane plots of plasmaspheric density from the dynamic global core plasma model (DGCPM) [Ober et al., 1997]. Results from
two simulations are shown, one with a prescribed convection electric field description (Figure 6a) and one with an electric field that is self-consistently calculated from the inner magnetospheric field-aligned currents produced by a simulation of energetic ring current plasma (Figure 6b). Both plots are for the same instant during the recovery phase of the 17 April 2002 magnetic storm. Details of the computational setup for these results are discussed by Liemohn et al. [2004].

Figure 6a yields the typical smoothly varying teardrop plasmapause with convection drainage plume morphology first modeled by Grebowsky [1970]. Figure 6b exhibits several features that resemble the plasmaspheric notches seen in the IMAGE EUV data. At ~15 LT there is a small indentation in the plasmapause; near 18 LT is a V-shaped depletion corresponding to the wrap of the drainage plume around the storm-time plasmapause; and at ~21 LT is yet another depleted notch within the wrapped up plume structure. These low-density regions are not seen in Figure 6a. The initial conditions and the ionospheric source and loss terms for these two simulations are exactly the same; the only difference is the ionospheric source and loss terms for these two simulations are shown, one with a prescribed convection electric field description (Figure 6a) and one with an electric field that is self-consistently calculated from the inner magnetospheric field-aligned currents produced by a simulation of energetic ring current plasma (Figure 6b). Both plots are for the same instant during the recovery phase of the 17 April 2002 magnetic storm. Details of the computational setup for these results are discussed by Liemohn et al. [2004].

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The electric potential vortices appear as a consequence of the injection of hot plasma sheet ions into the ring current region. Figure 7 gives a schematic illustration of this process. Influxes of particles create localized pressure peaks that must have field-aligned currents on the eastward and westward ends of the peak to close the asymmetric ring current loop. These field-aligned currents produce wells and peaks (eastward and westward ends, respectively) in the ionospheric electric potential pattern, which in turn can be mapped back out to the magnetosphere and alter the plasma flow through near-Earth space. The plasma motion is a clockwise flow around the electric potential peak (westward end) and a counterclockwise flow around the well (eastward end). The net result is a radially outward flow between the peak and the well and inward flows to the outside (in the azimuthal direction) of the well-peak pair. As the hot ion pressure peak drifts around the dusk side of the inner magnetosphere, the associated potential structure will also move westward through the region, eventually dissipating on the dayside.

The cold, plasmaspheric particles, which have essentially no magnetic drift, are therefore a tracer of the time history of the convective drift pattern. The formation of a notch in the plasmapause greatly depends on the local time location and extent of the hot ion injection. During a storm, there are many successive injections from the plasma sheet into the inner magnetosphere, which could cause numerous indentations and undulations in the plasmapause. Of course, this ring current-induced deformation of the plasmapause is highly dependent on the ionospheric conductance, which regulates the strength of the resulting ionospheric potential pattern through Ohm’s law. This may contribute to why notches appear during certain disturbed times and not others. A more rigorous computational analysis of notch formation is planned for the near future.

### 3. Notch Refilling

The conversion of EUV observations to pseudodensity, mapping into the magnetic equator, and tracking of features makes it relatively easy to follow changes in notch content as it evolves. Notches are often found to persist as an identifiable structure for an extended period of time [Sandel et al., 2003]. Figure 8 shows a sequence of images that extends across the entire lifetime of a notch that formed on 31 May 2000, during recovery from a moderate storm (Kp max = 4+). The first image was taken at 0859UT and is shown in Figure 8 as 0000 hours. The following images to the right show the time in hours and minutes relative to this first image time. The notch remains a prominent feature for nearly 32 hours before refilling. In order to estimate the filling rate, weighted averages of pseudodensity in a region

![Figure 7](image_url)
obtained a somewhat lower value of 30–40 cm
during the third orbital pass when the notch is centered from
for L = 4. At geosynchronous orbit
the areas considered.
function is the area represented by each image element in
extend in 0.5 intervals from L = 2 to L = 3.5 and for one
shown in the second panel of Figure 8 by the red boxes that
across the three regions illustrated by the box outlines
shown on the image at 0140 hours.
centered on the notch are computed and then followed in
time. The regions for which pseudodensity is averaged are
shown in the second panel of Figure 8 by the red boxes that
extend in 0.5 intervals from L = 2 to L = 3.5 and for one
hour on either side of the notch center. The weighting
function is the area represented by each image element in
the areas considered.

The weighted density as a function of time for this
notch is shown in Figure 9 and is found to vary consider-
dably during the three IMAGE orbital passes when the notch
can be followed. During the first 5 hours and from the
innermost range to the outermost, refilling rates are 5.5 ±
innermost L shell range are essentially constant, while
densities in the outer two L shell ranges rise at similar
rates. During this first orbital pass the notch is centered
between 18.1 hours and 21.8 hours MLT. During the second
pass the notch is located between 7.1 hours and 8.6 hours
MLT. While in this postdawn region the notch experiences a
modest increase in activity (Kp = 3) around 0000 UT on
1 June 2000. As a consequence, plasma is lost throughout
the notch during this period of modest activity with loss
rates of −101 ± 45.5 cm\(^{-3}\) d\(^{-1}\), −128 ± 29 cm\(^{-3}\) d\(^{-1}\), and
−128 ± 29 cm\(^{-3}\) d\(^{-1}\), respectively. Refilling is found again
during the third orbital pass when the notch is centered from
19.9 hours to 23.3 hours MLT. Refilling rates are 75 ±
18 cm\(^{-3}\) d\(^{-1}\), 139 ± 14 cm\(^{-3}\) d\(^{-1}\), and 80 ± 11 cm\(^{-3}\) d\(^{-1}\).
Unlike at the beginning of the observational period, there is
clear refilling across the whole L shell range during this
time period. As is expected, the averaged densities across all
times are highest for L shells in the range 2.0 ≤ L ≤ 2.5 and
lowest in the range 3.0 ≤ L ≤ 3.5.

The refilling rates derived from the EUV notch observ-
ations are similar to the refilling rate of ∼80 cm\(^{-3}\) d\(^{-1}\) for
L = 4.5 obtained by Carpenter et al. [1993]. Park [1973]
observed a somewhat lower value of 30–40 cm\(^{-3}\) d\(^{-1}\) for L =
4.5, while Chappell [1974] obtained a rate of ∼50 cm\(^{-3}\) d\(^{-1}\)
for L = 4. At geosynchronous orbit Lawrence et al. [1999]
measured an early time refilling at a rate of ∼0.6–12 cm\(^{-3}\)
d\(^{-1}\) and a later time refilling rate of 10–50 cm\(^{-3}\) d\(^{-1}\). By
using a dipole magnetic field, an estimate of ∼50 times
in flux tube volume and hence refilling rate might be antic-
pated between the Lawrence et al. [1999] observations and
those presented here. On the basis of that estimate, our early
recovery time refilling rates are comparable to those found at
geosynchronous orbit [see also Décréau, 1983, 1986; Higel
and Wu, 1984; Song et al., 1988].

4. Notch Drift

In addition to following the refilling of plasmaspheric flux tubes, the cross-field drifts of 18 notches have
been tracked. The MLT location of notch centers near L = 2.5
are first approximated manually. These locations are then
used as initial conditions for a least squares Gaussian
function fit to the azimuthal notch profile. The Gaussian-
derived notch centers are then followed in time. Table 1
shows the azimuthal drift rates as hours per day. A feature
drifting with the Earth’s rotation would be shown at a rate of
24 hours per day. Only one notch was observed to corotate with the Earth; the one observed on 28 May 2000. Most of
the remaining notches drift at a rate between 85% and 97%
of corotation. Two notches observed from 21–23 December
2000 were found to drift considerably slower at 44% and
74% the corotation rate, respectively. Figure 10 shows an
element of a notch that could be followed for three days.
The symbols show the MLT location of the (Gaussian-
derived) notch center during the observational period. The
solid line is a linear fit to the notch centers, which gives a
drift rate that is 91% of the corotation rate. Were the notch
to strictly corotate with the Earth, its location would follow
the dotted line. While this notch was followed for a longer
time than usual, the ability to approximate its subcorotation
with a linear function is typical. Even when minor varia-

Figure 8. Notch formed on 31 May 2000 sampled
throughout its life. Times shown are relative to the
time of the first image of 0831 UT on this day. It can be seen that
the notch extends across roughly 2 Re in radial distance and 2
hours MLT in EUV images. A weighted average of
plasmaspheric pseudodensity is computed for each image
across the three regions illustrated by the box outlines
shown on the image at 0140 hours.

Figure 9. Weighted average density as a function of time
plotted for the event shown in Figure 8. Weighted averages
are computed for the 0.5 L and 2 hour bins that follow the
notch center. Shaded bars correspond to linear fits to each
segment of average densities, indicating an initial gradual
increase, then minor storm-related decrease, and then more
pronounced increase at the end of the event.
tions away from a linear fit are found, an overall linear drift with time dominates the behavior of a notch. In addition, notches often substantially maintain their spatial shape during their lifetime. Some of the apparent changes in notch structure may be attributed to changes in observing geometry. A closer examination of the evolution of notch shape is left for subsequent study.

[21] Burch et al. [2004] have proposed that subcorotation of the plasmasphere is driven by subcorotation of the ionosphere. They go on to propose that the ionospheric disturbance dynamo drives ionospheric motion relative to corotation as described by Blanc and Richmond [1980]. Burch et al. [2004] tested their hypothesis by comparing ionospheric drift measurements from the DMSP spacecrafts against EUV derived plasmaspheric drift. The present notch measurements offer another opportunity to test this hypothesis. Ion Drift Meter (IDM) observations from the DMSP spacecraft numbers F12, F13, and F15 have been used to obtain average drift for time periods when a DMSP orbit passes within the L shell range $2 < L < 3$ and within 2 hours MLT of the notch location as observed by IMAGE EUV. IDM drift measurements during these conjunctions are averaged and included in Table 1. The relative correspondence between derived notch drift rates and ionospheric drift rates can be seen in Figure 11. Within the margin of error, most average ionospheric drifts are consistent with notch drift.

[22] Notably, that is not true for all cases. One such case, for 24–25 June 2000, is highlighted in Figure 12. Here, individual IDM drift measurements are compared to the derived linear notch drift. IDM drift measurements are shown in Figure 12 (top) where each symbol is an ionospheric drift measurement. Each grouping of symbols results from multiple IDM measurements during one DMSP pass near the notch location. The dotted line corresponds to corotation. The solid red line is the linear drift of the notch derived from EUV. Ionospheric drift rates are systematically slower than that of the notch. In Figure 12 (bottom) the relative magnetic longitude of the notch, in hours, is plotted through the observational period. The solid line is the linear fit. The dotted line indicates strict corotation. The plasmaspheric drift indicated by EUV is easily more than one standard deviation from the average ionospheric drift from IDM. That is also true for the notch observed on 3–5 July 2000.

[23] A possible explanation for the differences found between IDM and EUV drifts might be due to magnetic local time differences in the observations. As stated above, the IDM measurements included in ionospheric drift averages are within 2 hours MLT of the IMAGE spacecraft

Table 1. Plasmaspheric Notch and Ionospheric Drifts

<table>
<thead>
<tr>
<th>Dates in 2000</th>
<th>IMAGE/EUV (h d$^{-1}$)</th>
<th>DMSP/IDM (h d$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 May</td>
<td>22.2 ± 0.12</td>
<td>21.2 ± 1.5</td>
</tr>
<tr>
<td>28 May</td>
<td>24.0 ± 0.09</td>
<td>...</td>
</tr>
<tr>
<td>31 May to 1 June</td>
<td>22.4 ± 0.08</td>
<td>22.5 ± 3.4</td>
</tr>
<tr>
<td>14–15 June</td>
<td>20.4 ± 0.07</td>
<td>24.3 ± 3.7</td>
</tr>
<tr>
<td>16–17 June</td>
<td>22.6 ± 0.08</td>
<td>24.7 ± 1.4</td>
</tr>
<tr>
<td>24–25 June</td>
<td>23.2 ± 0.06</td>
<td>21.0 ± 0.5</td>
</tr>
<tr>
<td>30 June</td>
<td>21.6 ± 0.07</td>
<td>20.5 ± 20.5</td>
</tr>
<tr>
<td>1 July</td>
<td>22.5 ± 0.13</td>
<td>24.1 ± 1.8</td>
</tr>
<tr>
<td>3–5 July</td>
<td>22.6 ± 0.11</td>
<td>16.6 ± 1.0</td>
</tr>
<tr>
<td>6–9 July</td>
<td>22.2 ± 0.06</td>
<td>...</td>
</tr>
<tr>
<td>12–14 July</td>
<td>21.9 ± 0.64</td>
<td>22.6 ± 1.1</td>
</tr>
<tr>
<td>27–28 July</td>
<td>20.7 ± 0.11</td>
<td>22.0 ± 1.3</td>
</tr>
<tr>
<td>30–31 July</td>
<td>22.8 ± 0.05</td>
<td>21.0 ± 21.0</td>
</tr>
<tr>
<td>6 August</td>
<td>19.5 ± 0.76</td>
<td>...</td>
</tr>
<tr>
<td>6–10 August</td>
<td>21.9 ± 0.07</td>
<td>...</td>
</tr>
<tr>
<td>21–22 December</td>
<td>10.5 ± 0.08</td>
<td>...</td>
</tr>
<tr>
<td>22–23 December</td>
<td>17.8 ± 0.16</td>
<td>...</td>
</tr>
<tr>
<td>28–31 December</td>
<td>22.1 ± 0.10</td>
<td>21.8 ± 1.1</td>
</tr>
</tbody>
</table>

Figure 10. A notch center tracked across 3 days in August 2000 and shown as pluses. The solid line is a linear fit to the azimuthal notch drift at $2.19 ± 0.07$ h d$^{-1}$. The dotted line indicates corotational drift.

Figure 11. A scatterplot for EUV-derived plasmaspheric and IDM-derived ionospheric drifts. Error bars are drawn one standard deviation to either side of the average drifts.
location relative to the long-term drift. No such dependence was found. Observational geometry was also considered as a possible source of apparent short-term shifts in notch position. In a format similar to Figure 12, the spacecraft angular location relative to the plane of the notch and the rate of spacecraft motion transverse to the plane of the notch were examined along side the short-term shifts in notch position relative to the long-term trend. The idea here is that an observing location out of the plane of a notch might result in a systematic error in locating the notch in magnetic longitude. Similarly, the rate of motion of the observing location toward or away from the notch might lead to a systematic increase or decrease of the apparent rate of motion of a notch. Again, no such systematic correlation could be found to explain these short-term shifts.

[25] Another explanation for the notch (and, in general, plasmaspheric) subcorotation is the dawn-dusk asymmetry of the electric potential pattern [e.g., Lu et al., 1989; Boonsiriseth et al., 2001; Ridley et al., 2004]. For instance, Lu et al. [1989] found that the potential difference from the pole to the equator along the dusk meridian is typically 1.5 times larger than the potential difference along the dawn meridian. Ridley et al. [2004] explained this asymmetry as a result of the Hall conductance gradient at the terminators. In a three-dimensional Ohm’s law [Amm, 1996], there is a term proportional to the product of the meridional (north-south) electric field and the azimuthal (east-west) gradient of the Hall conductance. The net effect of this term is to reduce the magnitude of the duskside potential peak and increase the size of the duskside potential well (compare Ridley et al. [2004, Plates 4 and 6]). For nominal, nonstorm-time conductance values, Ridley et al. [2004] found that the duskside potential minimum was 23% larger than the dawnside potential maximum. A similar term in Ohm’s law that includes the azimuthal gradient of the Pedersen conductance yields an asymmetry of only 1% or 2% in the opposite direction (that is, a bigger duskside peak). The potential pattern asymmetry results in a stronger sunward convection on the duskside of the magnetosphere than on the dawnside, which is a difference not accounted for in standard two-cell convection patterns. The symmetric convection scenario leads to subcorotative flow on the duskside and supercorotative flow on the dawnside, with no net influence of convection on the drift period along closed drift paths (in steady state). However, the convective asymmetry creates a larger decrease on the duskside and a smaller increase on the dawnside, resulting in drift periods longer than 24 hours (that is, subcorotation). Liemohn et al. [2004] show that the inner magnetospheric component of the dawn-dusk asymmetry varies with storm phase (in the self-consistent electric field results), indicating that the subcorotation effect is modulated by field-aligned current and conductance variations. The disturbance dynamo discussed by Burch et al. [2004] also causes subcorotative drift periods. Both effects will cause the same net westward flow in the DMSP drift data. A determination of the relative contribution of these two effects is beyond the scope of this paper and intended for a later study.

5. Discussion and Conclusions

[26] Notches are one of the remarkable large-scale structural features of the plasmasphere, only recognized after

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**Figure 12.** (top) Drift rate derived from the IDM on DMSP satellites as a function of time on 24–25 June 2000. Each collection of symbols represents a separate DMSP pass through the vicinity of the notch in space and time. The dotted line corresponds to strict corotation. The red line is the notch drift derived from the EUV instrument. (bottom) Magnetic drift of the notch relative to the initial time of the observation period. The solid line is a least squares fit to the notch location. The dotted line represents strict corotation. Green symbols are for dayside notch locations, while red symbols are for the nightside.
flight of the remote sensing EUV instrument on the IMAGE spacecraft. Notches are characterized by nearly radial cavities in plasma density that often extend over 2 \( R_E \) in the magnetic equator and from a tenth of an hour to two hours or more in MLT. The notch density cavity can extend inward to \( L = 1.6 \) or less and is sometimes found to be transiently “capped” at the outer plasmaspheric boundary by a thin, residual plasmaspheric plume. Excavation of plasmaspheric densities to such low altitudes is remarkable by itself and cannot be explained by global convection as evidenced in the work of Carpenter and Anderson [1992]. We speculate here that mesoscale electric field structures, possibly resulting from localized storm-time injection, are necessary to create these spatially deep features. Densities in a notch can be at least a factor of 5–10 lower than the adjacent notch walls. Notches appear to form following weak periods of enhanced convection on the westward edge and base of the plasmaspheric plume. They can maintain their form for several days during quite conditions. Notches are also capable of loosing plasma while maintaining shape during subsequent weak periods of increased magnetic activity.

[27] A central enhanced density prominence was found in about 22% of the notches identified in 2000. On 24 June 2000, a prominence was observed to form soon after or with formation of a notch. Evidence is presented here that this prominence may be indicative of a spatially localized injection of plasma sheet ions and the formation of enhanced mesoscale regions of opposite electric potential. These small-scale potential enhancements appear capable of locally drawing plasma out of the interior high-density region into the low-density notch through modification of the \( \mathbf{E} \times \mathbf{B} \) convection pattern. As discussed above, such small-scale potential structures may also result in localized inward convection of plasma, possibly leading to the low L shell penetration of notch features. Although not presented, notch prominences do not necessarily stay centered in the notch even though the notch itself maintains its general shape. In two cases, interior prominences are observed to drift westward relative to the notch, later merging with the notch interior wall.

[25] The large, low-density region of a notch lends itself to the study of plasmaspheric refilling and examination of cross-field drift over extended periods of time. One refilling period was examined closely. During the event on 31 May and 1 June 2000, early changes in average density in the innermost L shell range are somewhat mixed with little overall refilling. The middle and outer L shell range, however, show a similar rate of refilling in the range of 47–49 cm\(^{-2}\) d\(^{-1}\). Refilling between 2 and 3 times this rate is observed on the second orbital pass in all L shell ranges. This last period of early time refilling is observed when the densities are higher than that present for the first orbital pass observing period. These refilling ranges are consistent with those reported by Lawrence et al. [1999] and others as discussed above.

[29] Of some interest is the loss of plasma in the innermost L shell range (2.0 \( \leq L \leq 2.5 \)) during the modest increase in magnetic activity to Kp = 3 near the start of 1 June 2000. On the basis of Carpenter and Anderson [1992], the plasmapause might be expected to erode inward to \( L = 3 \) for this level of activity. However, essentially the same rate of plasma loss is seen inside that L shell as is seen outside. Convective plasma loss cannot explain what is found inside of L = 3. Carpenter [1962] is the first to report this type of plasma loss inside a storm-time plasmapause. Drainage into the ionosphere is another avenue for plasma loss, which was first proposed by Park [1973]. This dayside plasma loss may also relate to the nightside density loss inside the storm-time eroded plasmapause found by Carpenter [1995]. Successful explanation of this low L shell plasmaspheric erosion will also need to operate near dawn as found here.

[30] As a plasmaspheric feature extended in L shell, notches directly support the examination of convective drift across a significant range of L shells. Table 1 summarizes our findings for 18 notches observed during 2000. Only one of these notches was found to drift with the rotation of the Earth. In two cases, the plasmasphere drifted much slower, as slow as 44% of corotation. We find that a notch most often drifts eastward at a rate of 85–97% of corotation. The only conclusion we can reach is that the plasmasphere usually lags corotational motion; however, the slippage is often not large. Burch et al. [2004] has suggested that westward ionospheric drift is responsible for slowing the corotational motion of the plasmasphere. Just as in this cited study, we have obtained IDM ionospheric drift measurements for 12 of 18 notches. One standard deviation error estimates for these ionospheric drifts suggest that most are consistent with our notch drift rates.

[31] For two of the notches studied here, the IDM drift rates are significantly slower than found using EUV. The implication is that the explanation for subcorotational drift of the plasmasphere may be more complex than currently thought. In this regard, we note the works of Lu et al. [1989], Boonsiriseth et al. [2001], Ridley et al. [2004], and Liemohn et al. [2004] may provide an additional explanation for subcorotational drift. These works collectively suggest that Hall conductance gradients at the terminators cause a dawn-dusk electric potential asymmetry, yielding a net subcorotational plasmaspheric drift that is storm phase–dependent.

Appendix A

[32] Observed EUV instrument counts are converted to column density [Sandel, private communication] using the following equation (A.1):

\[
N = a \times 10^{20} \frac{\text{cm}^{-2}}{\text{pixel}}.
\]

where \( N \) is the He\(^+\) column abundance in \( \text{cm}^{-2} \), \( a \) is the EUV signal in counts/pixel for a 10-min integration, and \( F \) is the solar irradiance at 30.4 nm in units of photons \( \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \). Solar irradiance is obtained from the SOLAR2000 irradiance model [Tobiska, 2004].

[33] Column integrated density is converted to pseudo-density by dividing by an estimate of the distance along the line of sight that contributes most to the image intensity at each location in the field of view. Because of rapidly falling densities in the plasmasphere with increasing L shell, the innermost regions penetrated by a given line of sight will contribute most to the observed 30.4 nm intensity [Sandel et al., 2003]. The EUV imager spatial resolution in the
equatorial plane while observing from apogee is about 0.1 \( R_E \), therefore that distance along the line of sight when passing within 0.1 \( R_E \) of the innermost L shell reached is divided into the column integrated density for each position in the EUV field of view. A sketch describing this influence is shown in Figure A1 along with a typical example of how this effective integration length changes with line of sight below a high-latitude observing location. [34]

By choosing observing periods when the IMAGE spacecraft is at high latitude (>60 degrees magnetic latitude) and relatively far from perigee (>4 \( R_E \) geocentric distance), the regions dominating the intensities observed in EUV images are relatively close to the magnetic equator. Relatively little change in density within the plasmasphere is anticipated along magnetic field lines near the equator [Gallagher et al., 2000; Reinisch et al., 2004], therefore EUV images are next mapped to the dipole magnetic equator [Sandel et al., 2003]. Dipole coordinates are used, since distortions from dipole are small close to the Earth during the periods of quiet geomagnetic activity examined in this study. [35]

The quantitative accuracy of the pseudodensity calculation has been tested by comparison to a known density. The dynamic global core plasma model (DGCPM) [Ober et al., 1997] was used to simulate a storm-time recovery period on 10 June 2001. The simulation resulted in a nightside, narrow plume and otherwise normal plasmasphere with a relatively sharp plasmapause boundary. This equatorial distribution of plasma was then used to define densities along the magnetic field. This run of DGCPM does not include an ionosphere and is limited to modeling L shells beyond 2; therefore no model ionosphere is included in this test. Simulated EUV images through this modeled environment were then produced for satellite positions at a distance of 8 \( R_E \) and at magnetic latitudes of 60°, 70°, 80°, and 90°. Pseudodensities where then computed for each image and compared to the original density distribution. Accuracy improved notably with increasing latitude, especially in the region viewed on the far side of the Earth. Most derived densities are within about 50% of the original, but vary by as much as a factor of nearly 10 in localized regions. Density at a sharp plasmapause tended to be underestimated. Densities just inside the plasmaspheric plume, in a low-density channel overdraped by the plume, are overestimated. Naturally, densities in the Earth’s shadow are underestimated by the pseudodensity calculation.

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