JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 112, A05227, doi:10.1029/2007JA012298, 2007

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Smooth electron density transition from plasmasphere to the subauroral region

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Received 25 January 2007; revised 27 February 2007; accepted 7 March 2007; published 30 May 2007.

[1] Upper hybrid resonance (UHR) noise band and the nonthermal continuum (NTC) radiation were routinely observed by the radio plasma imager (RPI) onboard the IMAGE satellite when it transited the plasmasphere and subauroral regions. The lower cutoff frequencies of the UHR band and the NTC radiation provide an estimate of the electron plasma frequencies along the satellite orbit. A steep electron density gradient, which defines the plasmapause, was commonly observed when IMAGE transited from the plasmasphere to the subauroral region or vice versa. It appears however that, on many occasions, the electron density transition from the plasmasphere to the subauroral region is smooth without a clear signature of the plasmapause. Such smooth transitions can occur at various magnetic local times. The events presented in this study were observed after geomagnetic activities had been quiet for 2 or more days with Kp primarily less than 3. The smooth density transitions from the plasmasphere to the subauroral region may be an observational evidence of the suggested plasmaspheric wind.

Citation: Tu, J., P. Song, B. W. Reinisch, and J. L. Green (2007), Smooth electron density transition from plasmasphere to the subauroral region, *J. Geophys. Res.*, *112*, A05227, doi:10.1029/2007JA012298.

1. Introduction

[2] The plasmasphere is a toroidally shaped plasma region of the near-Earth magnetosphere populated with cold (temperature $\leq$ 1 eV) and dense (10^1–10^4 cm^{-3}) plasma. The plasmasphere is typically bounded by the plasmapause, a region of a sharp density transition from the inner high density region to the outer low density region [*Lemaire and Gringauz,* 1998, and references therein]. It is believed that the plasmapause results from the interplay of the corotation and magnetospheric convection of the plasma together with plasmasphere refilling processes [*Nishida*, 1966]. In this paradigm, the plasmapause coincides with the last closed equipotential (LCE) under steady-state conditions. The LCE separates the inner region where the plasma basically corotates with the Earth and the outer region where the magnetospheric convection dominates. The magnetic flux tubes inside the corotation region can be supplied with plasma continually from the ionosphere, building up to an equilibrium density distribution and resulting in relatively high plasma densities [e.g., *Singh and Horwitz*, 1992]. The sunward convecting flux tubes outside the corotation region will drain their plasma toward the magnetopause, and thus those flux tubes have significantly lower densities [e.g., *Carpenter and Lemaire*, 1997].

[3] The above physical description of the plasmapause formation and the typical configuration of the plasmasphere with a bounding plasmapause are often presented when discussing the plasmasphere. Such description for the plasmasphere, with the recognition of the complicated density structures and dynamic processes in the plasmapause region by later observations [e.g., *Horwitz et al.*, 1990; *Moldwin*, 1997], establishes a perpetuating impression that the plasmasphere always has a boundary where the density drops sharply when moving outward from the plasmasphere. Hence a number of studies have been conducted to develop an empirical relationship between the plasmapause location and the Kp index or other geomagnetic activity indices using in situ plasma density measurements [e.g., *Binsack*, 1967; *Carpenter and Anderson*, 1992; *Moldwin et al.*, 2002; *O'Brien and Moldwin*, 2003]. Nevertheless, observations of smooth plasmaspheric density variations extended to about L = 7 or beyond have been reported previously [e.g., *Chappell*, 1972; *Corcuff et al.*, 1972; *Kowalkowski and Lemaire*, 1979; *Carpenter and Anderson*, 1992; *Tu et al.*, 2006], implying an extended plasmasphere with either the plasmapause located beyond L = 7 or smooth density transition to the subauroral region without identifiable signatures of a sharp plasmapause boundary. Such smooth transition is possible if the magnetospheric convection is very weak so that the corotation dominates to a large radial distance. However, little attention has been paid to such features of the plasmasphere density profiles.

[4] In this study, we present observations by the radio plasma imager (RPI) on the IMAGE satellite that show, at certain times, that electron densities vary smoothly from over 4000 cm^{-3} in the region of $L \leq \sim 2$ (inner plasmasphere) to less than 10 cm^{-3} in the region of $L \geq 10$ (subauroral region or polar cap). A sharp plasmapause is not identifiable from the electron density variations in those

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0148-0227/07/2007JA012298$09.00

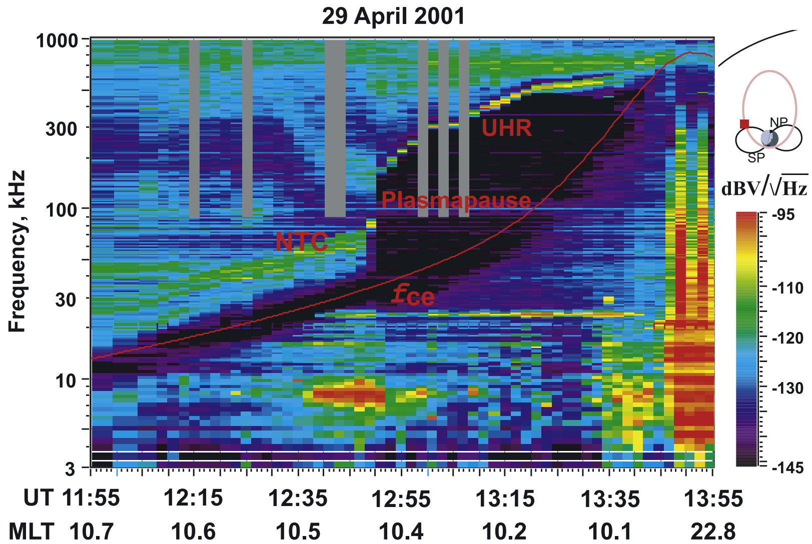

Figure 1. An electric field dynamic spectrum measured by IMAGE RPI from 1155 to 1355 UT on 29 April 2001, showing a UHR band and the NTC radiation. The red line is the electron gyrofrequency determined from the T96 magnetic field model [*Tsyganenko*, 1995]. The gray strips indicate frequencies and times when no passive data were measured from RPI. The IMAGE orbit configuration is shown on the upper right corner.

cases. Such smooth density transitions from the plasmasphere to the subauroral region can be observed at various magnetic local times. We use "subauroral region" instead of "plasmatrough" because the smooth variation of the electron densities often extends to the regions close to the auroral latitudes in the smooth transition events. The events presented in this study were observed during low Kp periods (Kp $\leq$ 2) when the interplanetary magnetic field (IMF) B_z was primarily northward or steadily negative, presenting challenges to empirical plasmapause models with the Kp dependence. The present observations have significant implication to the plasma dynamics in the plasmasphere.

2. Image RPI Passive Measurements

[5] The IMAGE was in a polar orbit with an orbit period of 14.2 hours so that it traversed the plasmasphere and subauroral region about two times per day. The data used in the present study are primarily from the electric field measurements of the radio plasma imager (RPI) on the IMAGE spacecraft [*Burch et al.*, 2001]. The RPI instrument alternated between making passive electric field measurements and radio sounding measurements. Each of those modes of operation is analyzed and displayed differently. The design and measurement characteristics of the IMAGE RPI have been described in detail by *Reinisch et al.* [2000]. In this study, we primarily use passive measurements of the IMAGE RPI that monitored the natural plasma wave environment around the satellite. Those natural plasma wave signals are displayed in conventional frequency-time electric field spectrograms (referred to as dynamic spectra) [e.g., *Green and Reinisch*, 2003] with the analysis software known as BinBrowser [*Galkin et al.*, 2004]. Typical features on an RPI dynamic spectrum are a narrow upper hybrid resonance (UHR) noise band and the nonthermal continuum (NTC) radiation. The lower cutoff frequencies of the UHR band and the NTC radiation provide an estimate of the electron plasma frequency f_{pe} or equivalently the electron density N_e ($N_e \propto f_{pe}^2$) [e.g., *Mosier et al.*, 1973; *Shaw and Gurnett*, 1980; *Benson et al.*, 2004]. On those dynamic spectra, there is often a sharp gradient (i.e., the plasmapause) in the variations of the frequencies of a UHR band or the lower frequency edge of the NTC radiation. Figure 1 displays an RPI dynamic spectrum in the period from 1155 to 1355 UT on 29 April 2001, showing the UHR band and the nonthermal continuum (NTC) radiation. The plasmapause is seen as a sharp gradient of the frequency of the UHR band when IMAGE moved from the subauroral region into the plasmasphere.

[6] In addition to the steep gradients and other complicated structures, on many occasions, the frequencies of the UHR band and the lower frequency edge of the NTC radiation vary quite smoothly without a clearly identifiable signature of the plasmapause. In the present study, a smooth transition case is defined as a density variation that does not drop by more than a factor of 3 within any $\Delta L \leq 0.5$ along the IMAGE orbit (*Carpenter and Anderson* [1992] defined the plasmapause at the location where a density drop by a factor of 5 or more occurs within $\Delta L \leq 0.5$ in the ISEE density profiles). A survey of a small database of the RPI passive measurements (from January to June 2001) indicates that such events occurred in about 10% of the time. It should be pointed out that although the observed density variations along an IMAGE orbit were not purely due to the L shell changes, the smooth density transition along the IMAGE orbit really indicates that the plasmapause did not exist in terms of the density variations at least in the longitude sector of the orbit. This argument is supported by the fact that along the similar passes of the plasmasphere and subauroral region, both the steep density gradient and the smooth transition were observed (comparing Figures 1 and 6). Additional support comes from the IMAGE Extreme Ultraviolet Imager (EUV) observations of the large diffusive

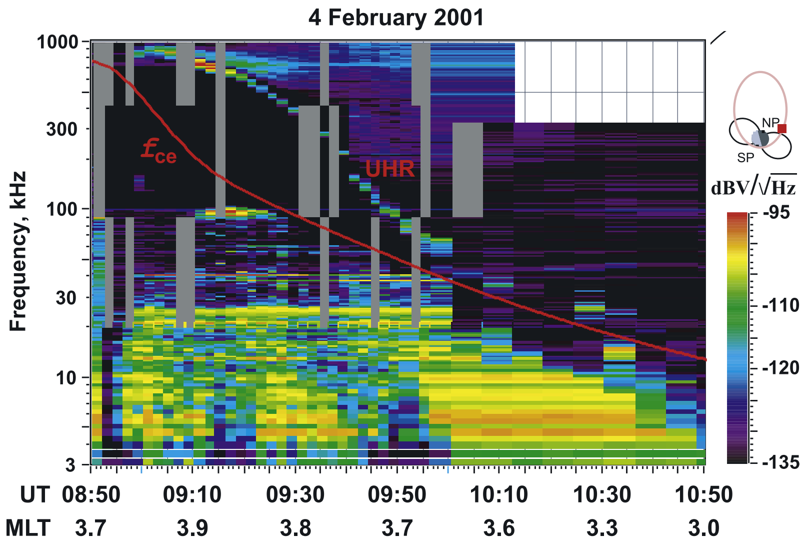

Figure 2. The same format as Figure 1 but for the period 0850–1050 UT on 4 February 2001.

plasmasphere before and after the smooth transition passes of the plasmasphere/subauroral region as will be shown by IMAGE EUV images.

3. Smooth Density Transitions

[7] In the following, we present three cases of the smooth density transition from the plasmasphere to the subauroral region ($L \geq 10$) or vice versa and examine the solar wind conditions under which those smooth transitions occurred.

[8] Figure 2 displays a dynamic spectrogram measured by the IMAGE RPI from 0850 to 1050 UT on 4 February 2001 along a nightside outbound pass. A UHR band is clearly seen with its frequency varying smoothly from about 0902 to 1025 UT, but the lower frequency edge of the NTC radiation is not identifiable on this dynamic spectrum. From the lower frequency cutoff of the UHR band, we derive the electron densities using the procedure described by *Benson et al.* [2004] and show the results in Figure 3. The orbit parameters are labeled under the abscissa. The dashed line displays the electron density variation along the IMAGE orbit as predicted by *Gallagher et al.* [2000] through their empirical model. The modeled density shows a plasmapause at about $L = \sim 4.5$. The solid dots represent in situ electron densities derived from the available RPI sounding measurements along this pass. It is seen that the passive and sounding measurements result in essentially identical electron densities. It is demonstrated in Figure 3 that the observed electron density varies smoothly from 9003.9 cm^{-3} (inner plasmasphere level) at 0902 UT to $\sim$1.77 cm^{-3} (subauroral region

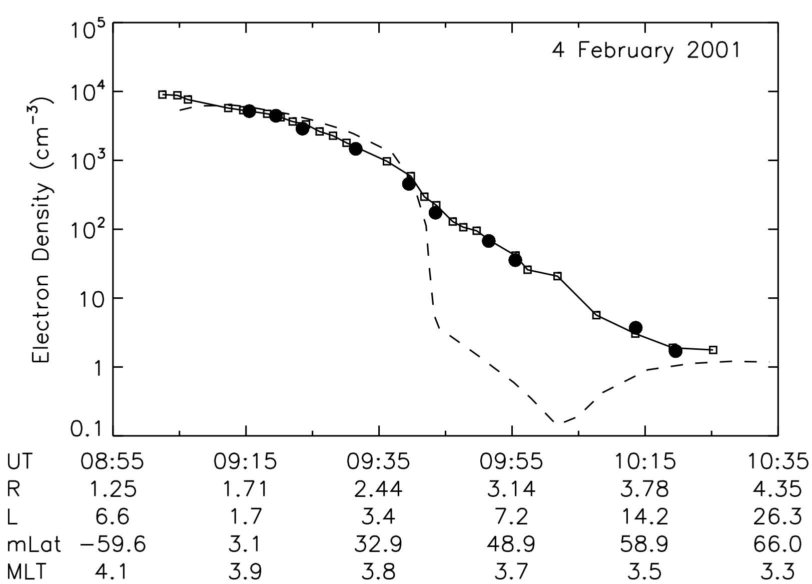

Figure 3. Variations of the electron densities along the IMAGE orbit derived from the lower frequency cutoff of the UHR band on the dynamic spectrum shown in Figure 2. The dashed line represents electron densities from empirical model of *Gallagher et al.* [2000]. The solid dots are in situ electron densities derived from the available sounding measurements.

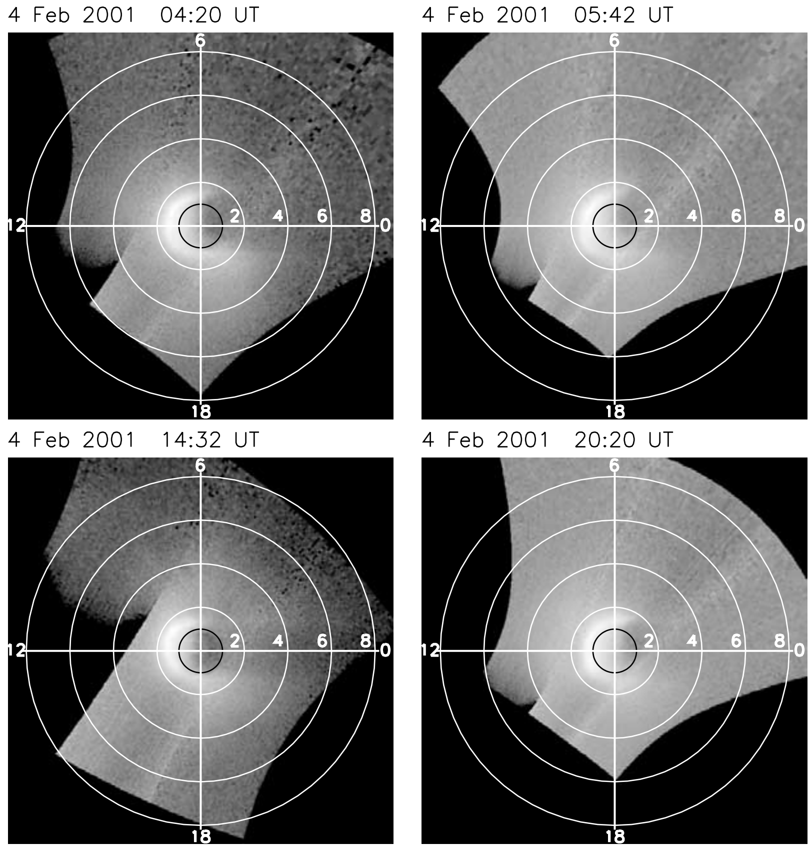

Figure 4. IMAGE EUV images of the plasmasphere in the equatorial plane taken at 0420 UT, 0542 UT, 1432 UT, and 2020 UT on 4 February 2001. The magnetic local noon is on the left, and solid circles indicate radial distance 2, 4, 6, and 8 R_E. The innermost black circle represents the Earth.

level) at 1025 UT. The IMAGE location decreased from $L = 1.86$ at 0902 UT to $L = 1.61$ at 0906 UT and then increased to $L = 19.63$ at 1025 UT. The density does not drop by more than a factor of 3 within any $\Delta L \leq 0.5$ along the orbit. This is an example of the smooth density transition from the plasmasphere to the subauroral region without the expected sharp plasmapause. We have examined global images of the plasmasphere taken by the Extreme Ultraviolet Imager (EUV) [*Sandel et al.*, 2000] on the IMAGE satellite. When the IMAGE was over the northern polar cap on 4 February 2001, the EUV images showed a large diffusive plasmasphere extending to the radial distance greater than 9 R_E in the equatorial plane. Figure 4 displays four IMAGE EUV images of the plasmasphere in the equatorial plane, taken at 0420 UT, 0542 UT, 1432 UT, and 2020 UT on 4 February 2001. The images on the first row (the second row) were acquired by the IMAGE EUV before (after) the smooth transition pass shown in Figure 3. From these and other images taken on 4 February 2001, we see a large diffusive plasmasphere in the radial distance extent greater than 9 R_E without the plasmapause signatures. Although one may argue that the plasmapause was located beyond 9 R_E radial distance, it is typically concluded that the region beyond 9 R_E radial distance is the subauroral region or plasmatrough because of the very low electron densities (below 10 cm^{-3}) there [e.g., *Carpenter and Lemaire*, 2004].

[9] It is interesting to examine geomagnetic activities and solar wind/IMF conditions for the above period of observations. Shown in Figure 5 are Dst index, Kp index, IMF B_z, and solar wind dynamic pressure, respectively, on 2–4 February 2001. The IMF B_z and solar wind dynamic pressure were measured by the ACE spacecraft in the upstream solar wind at XGSM = $\sim$230 R_E. Figure 5 indicates that the RPI density measurements in Figure 3 were made in a period of very quiet geomagnetic activities (delimited by two vertical lines) with Dst = $\sim$6 nT and Kp $\leq$ 0.3. The geomagnetic activity had been very quiet for about 3 days before the RPI measurements. The IMF B_z was primarily northward or close to zero for 2 days. The solar wind dynamic pressure, which is available only before 0900 UT on 3 February 2001, was less than 2 nPa.

[10] The above observation was made at about 3.7 magnetic local time (MLT) sector. The smooth transitions from the plasmasphere to the subauroral region can also be observed at other local times. In Figures 6 and 7, we display two events observed by the IMAGE RPI: one during the period of 1710–1910 UT on 27 April 2001 and another one during the period of 1740–2000 UT on 14 June 2001, respectively. The smooth transition on 27 April 2007 was observed about 2 days before the plasmapause observations shown in Figure 1. The IMAGE orbit in this period was quite similar to that in the period in Figure 1 because of negligible orbit precession within 2 days. This is a strong evidence that the smooth density variations along the

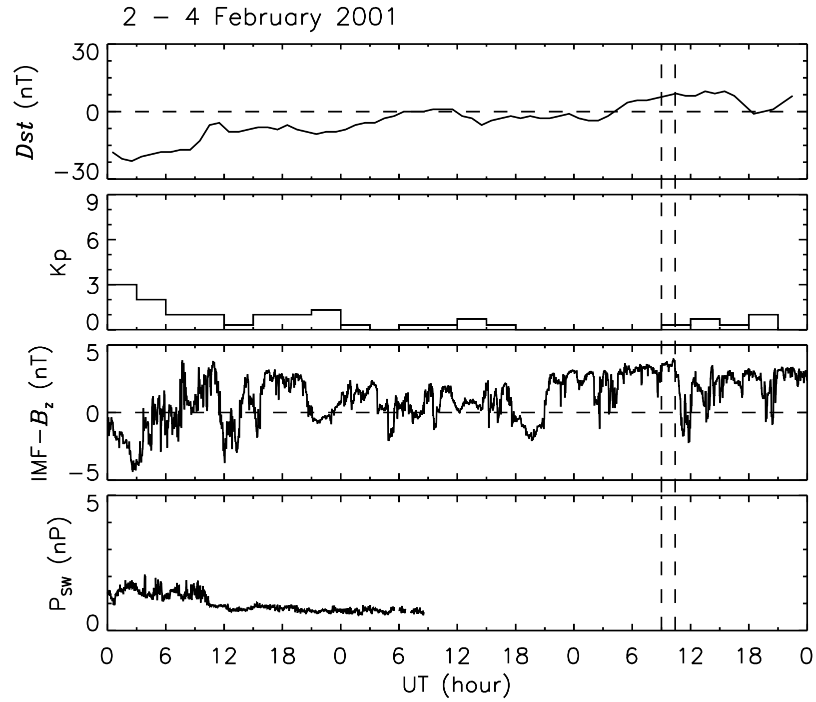

Figure 5. Variations of Dst index, Kp index, and IMF B_z from 0000 UT of 2 February 2001 to 0000 UT of 5 February 2001. Two vertical lines enclose the period of the density measurements shown in Figure 3.

IMAGE orbits are really the indication of the smooth transition from the plasmasphere to the subauroral region or vice versa without the identifiable sharp plasmapause signatures in terms of density variations. Otherwise, it is difficult to explain why along similar orbits the plasmapause can be observed along one orbit but not along another orbit.

[11] In the following, we present only the electron densities derived from the lower frequency cutoff of the UHR band and the NTC radiation but do not show the corresponding dynamic spectra for these two cases. Figure 6 shows the electron density variations along an inbound pass from low to high altitudes. For the period of the density measurements shown in Figure 6, the spacecraft moved from L = 10.05 at 1721 UT to L = 1.92 at 1842 UT and then reached L = 3.30 at 1856 UT. The magnetic local time (MLT) of the orbit segment was around 10.5 MLT. The electron density does not drop by more than a factor of 3 within any $\Delta L \leq 0.5$ along this pass, and thus the signature of a sharp plasmapause is not present, although the empirical model of *Gallagher et al.* [2000] predicts a plasmapause at L = ∼4.2 (dashed line). The same is true for the density variations displayed in Figure 7, which

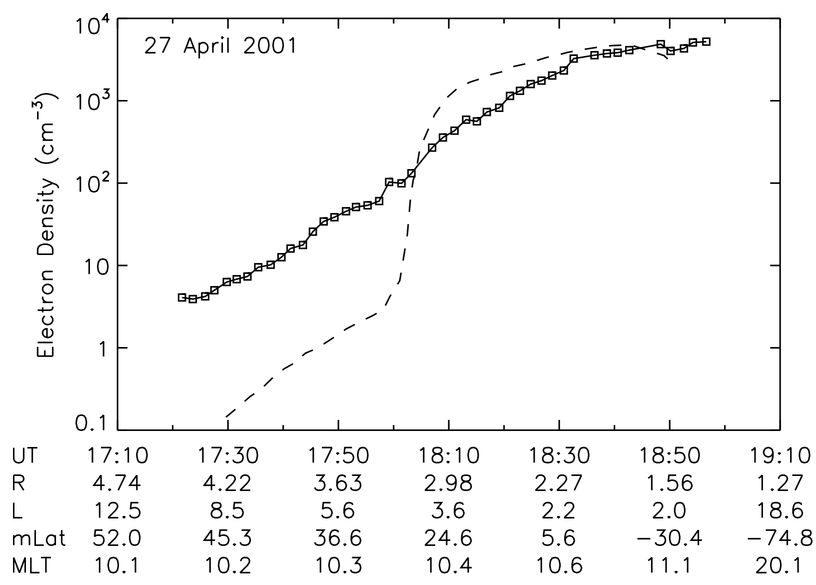

Figure 6. The same format as Figure 3 but for the period 1710–1910 UT on 27 April 2001 without the sounding measurements of the electron densities.

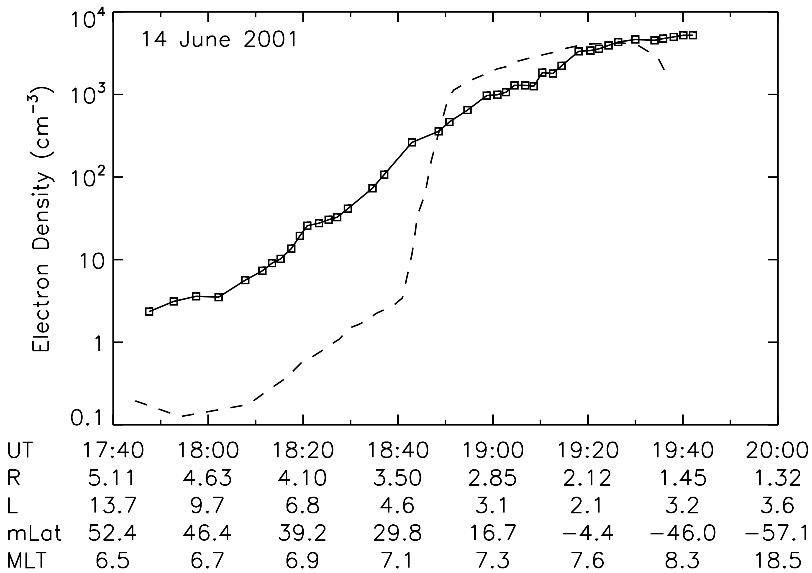

Figure 7. The same format as Figure 6 but for the period 1740–2000 UT on 14 June 2001.

were measured by the RPI along an inbound pass from high to low altitudes: IMAGE moved from L = 12.11 at 1747 UT to L = 2.02 at 1926 UT and then to L = 3.76 at 1942 UT. There is no steep density gradient observed along this orbit segment around 7.4 MLT (the empirical model shows a plasmapause at L = ~4.1). The IMAGE EUV images (not shown) acquired over the northern polar cap on 27 April 2001 and 14 June 2001 also displayed a large diffusive plasmasphere, implying that the smooth transitions might be a global feature of the plasmasphere on these 2 days.

[12] We also examine the geomagnetic activities and IMF conditions for the above two smooth transition events. In the same format as Figure 5, Figure 8 displays Dst index, Kp index, IMF B_z, and solar wind dynamic pressure for 3 days starting from 0000 UT of 25 April 2001 to 0000 UT of 28 April 2001. As can be seen from Figure 8, the smooth transitions shown in Figure 6 occurred during a prolonged period of very quiet geomagnetic activities. The Dst was close to zero, and Kp was less than 3 in about 2 days. The IMF B_z had been primarily positive for more than 2 days before the RPI measurements. The solar wind dynamic

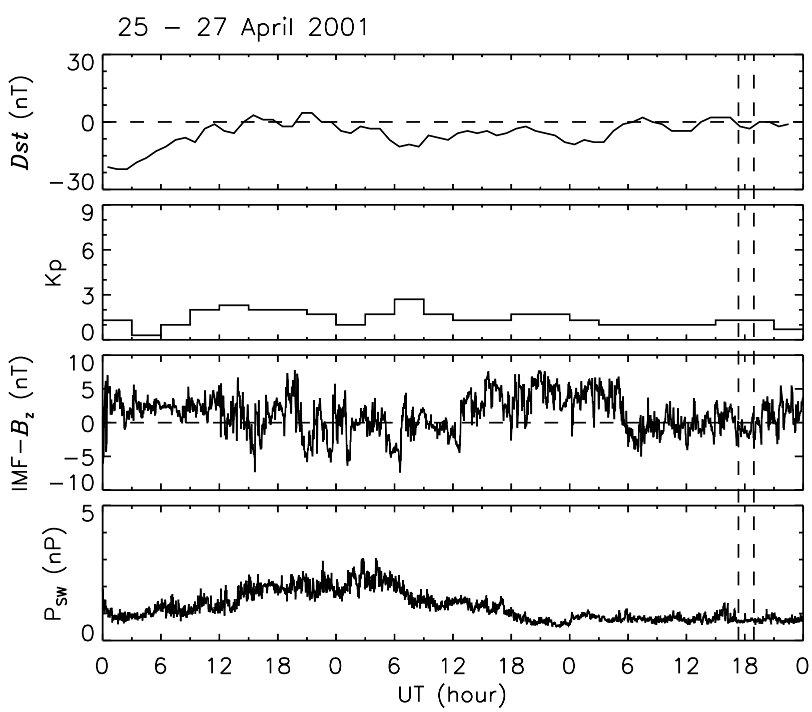

Figure 8. The same format as Figure 5 but for the period from 0000 UT on 25 April 2001 to 0000 UT of 28 April 2001.

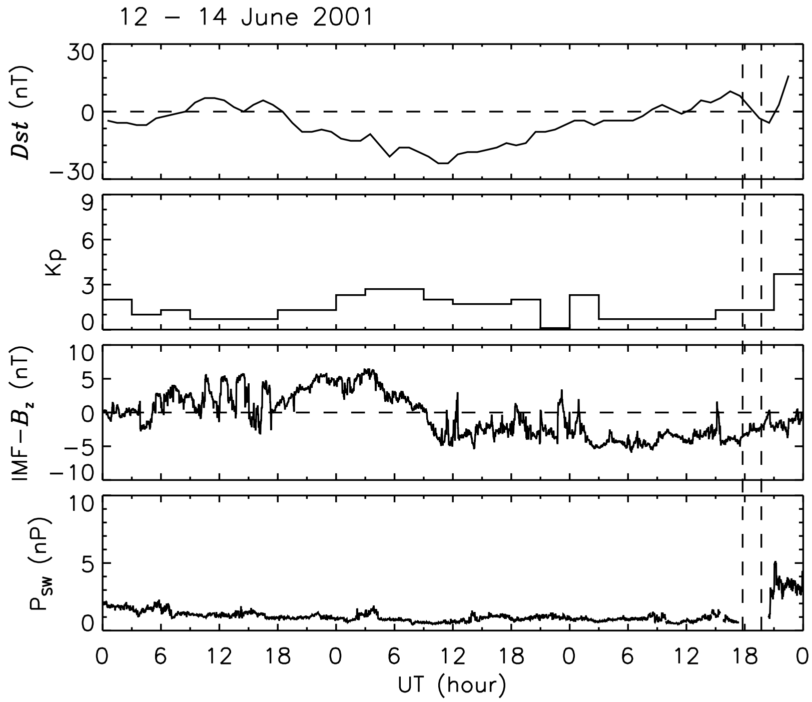

Figure 9. The same format as Figure 5 but for the period from 0000 UT on 12 June 2001 to 0000 UT on 15 June 2001.

pressure was less than 3 nPa. The 14 June 2001 case (shown in Figure 7) was also observed during very quiet period of geomagnetic activity with Kp = 1.7 and Dst close to zero, as demonstrated in Figure 9. However, the geomagnetic activities 1 day before the RPI measurements were moderate: Kp reached 3 and minimum Dst was −25 nT. The IMF B_z had remained negative and relatively steady for about 32 hours before the RPI measurements. The solar wind dynamic pressure had been small (less than 2 nPa) for almost 3 days.

4. Discussion

[13] The above IMAGE RPI observations have demonstrated that, at times, the plasmaspheric electron densities can smoothly transit from the plasmasphere to the subauroral region or vice versa without identifiable signatures of a sharp plasmapause along those IMAGE passes of the plasmasphere/subauroral region in terms of the density variations. The smooth transitions presented in this study occurred at various local times and were possibly a global feature of the plasmasphere. The smooth transition events presented occurred during prolonged periods of the quiet to moderate geomagnetic activities with Dst close to zero and Kp ≤ 3. The IMF B_z had been either northward for more than 40 hours or remained relatively steadily negative for more than 30 hours before the smooth transition events were observed. Observations of the extended plasmasphere have been occasionally reported in previous studies [e.g., *Chappell*, 1972; *Corcuff et al.*, 1972; *Kowalkowski and Lemaire*, 1979; *Carpenter and Anderson*, 1992; *Tu et al.*, 2006]. However, such phenomenon has not been investigated systematically because the plasmasphere is thought to be always bounded by the plasmapause.

[14] The plasmapause is usually identified as a steep gradient in the plasma density profiles, and the Kp dependence of the plasmapause location has been derived using the plasma density measurements [*Binsack*, 1967; *Carpenter and Anderson*, 1992; *Moldwin et al.*, 2002; *O'Brien and Moldwin*, 2003]. The smooth transitions that occur during periods of low Kp suggest that the Kp dependence of the plasmapause location derived from the plasma density measurements alone may not be valid if low Kp values remain for more than 24 hours. Recently, *Carpenter and Lemaire* [2004] suggested that the plasmapause region be called the plasmasphere boundary layer (PBL) to reflect the fact that the plasmapause is where the cool and dense plasmasphere overlaps with the hot ($\approx$100 eV–100 keV) and tenuous (≈ 1 cm^{-3}) plasma of the subauroral region or the plasma sheet or ring current. The term plasmasphere boundary layer (PBL) implies a persistent transition layer between the plasmasphere and subauroral region in terms of plasma temperature variations. Therefore plasma temperature may be a better quantity to identify the PBL, particularly during periods of low Kp values when the density variations show smooth transitions.

[15] The observed smooth electron density transitions from the plasmasphere to the subauroral region are important to the understanding of the plasma dynamics in the plasmasphere, particularly plasmapause formation mechanisms. The smooth transition is possible if the magnetospheric convection is very weak for a prolonged period and the effect of the plasmasphere corotation with the Earth dominates to large radial distances. The smooth density transitions may be also related to the convective or interchange instabilities in the magnetosphere [e.g., *Lemaire*, 1974; *Southwood and Kivelson*, 1987; *Brice*, 2001; *André and Lemaire*, 2006], particularly when the magnetospheric

convection does not diminish (e.g., for the case shown in Figure 7). *André and Lemaire* [2006] showed that the flux tubes in the plasmasphere beyond about $L \geq 2$ are convectively unstable during quiet geomagnetic activities because of the curvature of the convex geomagnetic field lines. As a consequence of the type 2 quasi-interchange motion of flux tubes, the equatorial plasma has an outward motion, which *Lemaire and Schunk* [1992, 1994] referred to as "plasmaspheric wind". This unstable outward plasma motion is mainly transverse to the convex magnetic field lines in the equatorial region of the plasmasphere, while it is dominantly field aligned at lower altitudes along the flux tubes. It corresponds to the type 2 quasi-interchange motion in Newcomb's seminal (but not well known) article [*Newcomb*, 1961]. The plasmaspheric wind, if it exists, implies of course that the plasmasphere would not be in hydrostatic equilibrium, as usually assumed, even after prolonged periods of quiet geomagnetic activity. The equatorial plasma streamlines in the region of $L \geq 2$ are thus not truly closed curves but consist of open spirals; that is, the plasmasphere is expanding slowly outward. The concept of the last closed equipotential (LCE) [e.g., *Nishida*, 1966] predicts the closed streamlines inside the LCE and the open streamlines outside. According to the LCE scenario, a well-defined sharp density gradient near the LCE will be developed after a prolonged period of quiet geomagnetic activities because of continuous refilling of the plasma from the ionosphere to the flux tubes inside the LCE. In contrast, there should be no well-defined sharp density gradient developed after several days of quiet geomagnetic activities due to the effects of the plasmaspheric wind [*Lemaire and Schunk*, 1992, 1994; *André and Lemaire*, 2006]. The smooth density transitions from the plasmasphere to the subauroral region may be an observational evidence of the suggested plasmaspheric wind. In addition, the smooth electron density transitions are not stable because they change to the density distributions with well-defined plasmapause when there are disturbances in the solar wind/IMF, providing opportunities to study the mechanisms of the plasmapause formation.

[16] The possible existence of the plasmaspheric wind due to the convective or interchange instabilities in the magnetosphere implies that the plasmapause formation is actually the consequence of the interplay of three processes: corotation, convection, and interchange instabilities, instead of only two processes (corotation and convection). The sharp density gradient, identified as the plasmapause, will evolve subject to the influences of these processes. However, except for a qualitative description about the level of the geomagnetic activities, quantitatively, we do not know how the density gradients vary in response to the changing geomagnetic activities or changing solar wind/IMF conditions. The corotation is fairly stable, but the convection is unsteady. Effects of the plasmaspheric wind are also variable because the onset conditions of the convective or interchange instabilities are influenced by the field-aligned density distributions in the plasmasphere that are time-dependent. We have to specifically clarify the conditions (e.g., Kp values and/or history or some measure of the solar wind/IMF conditions) for the onset of the plasmaspheric wind before we can quantitatively determine under what conditions there is (or not) distinct plasmapause in terms of plasmasphere density distributions.

[17] **Acknowledgments.** This work was supported by NASA under subcontract 83822 from the Southwest Research Institute and by NSF grant NSF-ATM 0518227 to the University of Massachusetts-Lowell. The ACE solar wind/IMF data were obtained from the CDAWeb system, and the Dst and Kp indices were provided by the National Geophysical Data Center. IMAGE EUV images were provided by IMAGE EUV team (requested through http://euv.lpl.arizona.edu/euv/data/index.html).

[18] Wolfgang Baumjohann thanks Joseph Lemaire and another reviewer for their assistance in evaluating this paper.

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