Plasmapause undulation of 17 April 2002

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[1] We report IMAGE EUV observations of a striking undulatory motion of the plasmapause that occurred on 17 April 2002, in which a large ripple propagated westward across the duskside plasmapause. From the plasmapause motion we infer a peak E-field of ≈3 mV/m associated with the undulation, and estimate the undulation's equatorial azimuthal speed to be 0.9 rad/hr ≈ 4 R_E/hr, corresponding to ≈1 km/s in the ionosphere (using an $R^{3/2}$ dependence to map from the equator). Because DMSP ion drift data at 850 km altitude show the presence of a subauroral polarization stream (SAPS) flow channel ≈1 km/s at the same location and time as the undulation, we assert that SAPS was responsible for removal of plasma during the undulation. The SAPS apparently formed in response to a 19:00 UT substorm onset. *INDEX TERMS:* 2712 Magnetospheric Physics: Electric fields (2411); 2768 Magnetospheric Physics: Plasmasphere; 2788 Magnetospheric Physics: Storms and substorms. **Citation:** Goldstein, J., B. R. Sandel, M. R. Hairston, and S. B. Mende (2004), Plasmapause undulation of 17 April 2002, *Geophys. Res. Lett.*, *31*, L15801, doi:10.1029/2004GL019959.

1. Introduction

[2] Since 2000 the IMAGE extreme ultraviolet (EUV) imager has routinely obtained global images of the plasmasphere [*Sandel et al.*, 2003]. EUV detects 30.4-nm sunlight resonantly scattered by plasmaspheric He^+ ions, producing images that capture the portion of the plasmasphere corresponding to electron densities above ≈40 cm^{-3} [*Goldstein et al.*, 2003c; *Moldwin et al.*, 2003]. Analysis of an EUV image often involves identifying a steep gradient in the He^+ distribution, and mapping its location to the equatorial plane [*Roelof and Skinner*, 2000], yielding global plasmapause curves that agree with in situ measurements to within a fraction of an Earth radius (R_E) [*Spasojević et al.*, 2003; *Moldwin et al.*, 2003].

[3] Because the plasmasphere is composed of cold (≈1 eV) plasma subject primarily to $E \times B$ drift, the location and shape of the plasmapause is a useful diagnostic of the inner magnetospheric convection field. It is well established that dayside magnetopause reconnection (DMR) during southward interplanetary magnetic field (IMF) imposes a dawn-dusk E-field that drives sunward convection in the inner magnetosphere. Consistent with this, sunward motions of the plasmapause in EUV images have been strongly correlated with intervals of southward IMF [*Goldstein et al.*, 2003a; *Spasojević et al.*, 2003; *Goldstein et al.*, 2003b]. There is also good evidence that auroral substorm dipolarizations provide a strong sunward push to the plasmaspheric plasma [e.g., *Carpenter and Smith*, 2001, and references therein]. In global EUV images, such substorm-driven plasmapause motion has not yet been directly or conclusively observed, although *Goldstein et al.* [2003a] argued that substorm E-fields probably contributed to an EUV-observed erosion event on 10 July 2000.

[4] During auroral activity, feedback between the ring current (i.e., innermost plasmasheet) and the ionosphere creates the subauroral polarization stream (SAPS) [*Foster and Burke*, 2002; *Anderson et al.*, 2001; *Burke et al.*, 1998]. Spatial separation between the inner edges of the ion and electron plasma sheets produces field-aligned currents (FAC) at the two edges that are completed by a poleward-flowing Pedersen current in the nightside subauroral ionosphere. The flow of this current through the low conductivity subauroral ionosphere produces strong poleward E-fields (which in turn can further reduce the ionospheric conductivity [*Anderson et al.*, 2001]). Thus, ionospheric SAPS are strong poleward E-fields found (on average) 3–5 degrees magnetic latitude (Λ) below the auroral oval, concentrated most strongly in the dusk/pre-midnight sector [*Foster and Vo*, 2002]. In the equatorial plane this maps to a radially-narrow (1–2 R_E) channel of westward flows (i.e., radial E-fields) that affects the plasmasphere by intensifying duskside convection [*Goldstein et al.*, 2003b].

[5] In this letter we report EUV observations from 17 April 2002 of a striking undulatory motion of the plasmapause consisting of the formation and removal of a duskside plasmapause bulge. We will provide observational evidence that a SAPS flow channel removed the bulge plasma, and speculate that a 19:00 UT substorm onset caused the global sunward convection enhancement responsible for the entire event.

2. Plasmapause Undulation

2.1. Plasmapause Motion

[6] Figure 1 shows IMAGE EUV observations from 19:05–20:37 UT on 17 April 2002. The top row contains EUV images, mapped to the magnetic equator. The color/intensity is proportional to line-of-sight-integrated He^+ column abundance, in arbitrary units. The plasmasphere is the green/white haze surrounding the Earth (drawn in the center). Each plot in the bottom row of Figure 1 shows the manually-extracted plasmapause from the EUV image directly above it. The image quality in Figures 1a–1d suffers from two problems. First, the images contain above-normal background noise (dark green speckling

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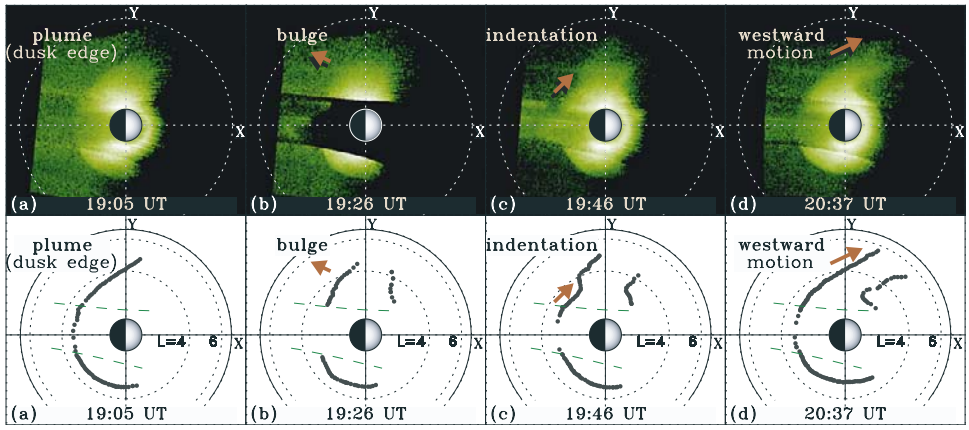

Figure 1. Four snapshots of the 17 April 2002 undulation, in which a duskside plasmapause bulge formed and was subsequently stripped away by a westward-propagating indentation. Upper: IMAGE EUV equatorial He^+ abundance. Saturated counts in the center camera (dashed lines, lower panel) and partial loss of dayside signal are both artifacts of sunlight contamination. Lower: Manually extracted plasmapause. Solid lines: X and Y axes (SM coordinates) and geosynchronous orbit. Dotted lines: L = 4, 6.

outside the plasmapause), probably due to the very disturbed geomagnetic conditions (see below). Second, due to the viewing geometry the images contain significant sunlight contamination, causing signal attenuation on the dayside, saturation or turning off of the center camera, and some streaking in the top 1/3 of the image. For reference, the center camera edges are indicated by the dashed lines in the bottom panels. Gaps in the extracted plasmapauses (lower panels) are where sunlight contamination prevented plasmapause identification. Manual plasmapause extraction involves some subjective uncertainty which we estimate (based on the work of *Goldstein et al.* [2003c]) to be $\approx 0.1L$ on the nightside where the plasmapause gradient is steep, and $\leq 0.4L$ near dusk.

[7] 17 April 2002 was the first day of a large geomagnetic storm; at 18 UT, Dst ≈ -98 nT and Kp > 6. (For more about the 17 April storm, see *Liemohn et al.* [2004].) Typical of these geomagnetic conditions, the plasmasphere in the 19:05 UT EUV image (Figure 1a) shows evidence of a prior period of erosion; the nightside plasmapause has both a sharp radial gradient and a smooth MLT-shape that is roughly circular (at $L \approx 3.3$) east of 2000 MLT and contains evidence of a drainage plume near dusk.

[8] Figures 1a–1d summarize the plasmapause undulation event. The strongest and most conspicuous motion was a ripple (i.e., azimuthal gradient in the plasmapause radius) that formed and propagated westward along the duskside plasmapause. At 19:26 UT (Figure 1b) the ripple was shallow, consisting of a mild 0.4 R_E bulge west of 2000 MLT, and a mild 0.4 R_E indentation east of 2000 MLT. After 19:36 UT the eastern edge of the ripple was steepened by a westward-propagating 1 R_E indentation that apparently stripped away the mild bulge. At 19:46 UT (Figure 1c) this indentation/ripple was located at 2000–2100 MLT. The formation and removal of the bulge produced a dramatic global undulatory motion of the duskside plasmapause that has been neither identified nor explicitly predicted in previous studies. Unlike typical erosion events seen by EUV [*Goldstein et al.*, 2003a] in which the plasmapause moved ≥ 2 R_E inward, the net inward displacement for the 17 April undulation was small; after the undulatory motion ended (20:37 UT, Figure 1d) the duskside plasmapause returned to its approximate original location (19:05 UT, Figure 1a).

2.2. Plasmapause Electric Field

[9] We used the technique of *Goldstein et al.* [2004] to infer for this event the electric field E_π, defined as the component of E-field tangent to the moving plasmapause. (Note E_π has contributions from both radial and azimuthal E-fields.) Figure 2a plots E_π vs. UT (vertical axis) and MLT (horizontal axis) between 18:04–21:28 UT on 17 April 2002. The times of the four snapshots in Figures 1a–1d are indicated by the four broken horizontal lines labeled a–d. E_π intensity (in mV/m) is given by the colorbar. Crude error-propagation analysis yields 0.1–0.2 mV/m uncertainty in E_π due to subjectivity in the manually-extracted plasmapause alone. Line plots of E_π vs. UT contain noise-like fluctuations of amplitude 0.4–0.5 mV/m, which we take as an estimate of the total uncertainty in E_π.

[10] For inward motion of the plasmapause, $E_\pi < 0$ (green, yellow, orange, or red); for outward motion, $E_\pi > 0$ (dark blue). Figure 2a shows that the 17 April 2002 event began at 19:05 UT (horizontal line 'a') with an indentation

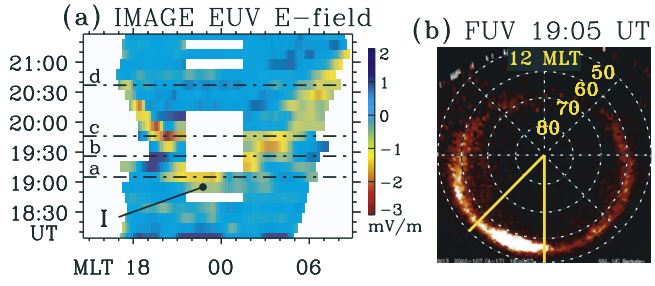

Figure 2. (a) Electric field E_π tangent to the moving plasmapause vs. UT and MLT. Colorbar gives strength in mV/m (white = no data). (b) IMAGE FUV SI13 electron aurora at 19:05 UT, vs. magnetic latitude (Λ) and local time (noon MLT at top). Substorm onset occurred 2100–2400 MLT (yellow lines).

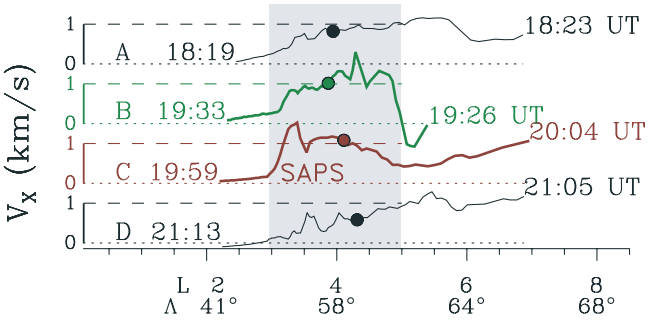

Figure 3. The 17 April DMSP F13 drift meter data (850 km altitude): sunward flow speed (km/s) vs. dipole L and Λ for 4 successive passes through duskside subauroral region. MLT of four intervals: (A) 1816–1818, (B) 1805–1808, (C) 1823–1831, (D) 1823–1901. SAPS (trace C) flows are evident at the same time and location as the plasmapause undulation.

('I') of the 2100–2400 MLT plasmapause with associated westward E-field $E_\pi \approx -1.2$ to -1.5 mV/m. After 19:05 UT, an effect propagated along the plasmapause both eastward and westward from this pre-midnight sector, producing the V-shaped signature in Figure 2a. (The vertex of the 'V' is at 'I'.) The westward-moving effect (the left half of the 'V') is the manifestation in E_π of the duskside undulation (Figure 1). Outward bulging of the post-dusk plasmapause (see Figure 1b) shows up as blue pixels ($E_\pi \approx 1.3$ mV/m) between 1900–2100 MLT during 19:16–19:26 UT. The approximately linear red/yellow ($E_\pi \approx -2$ to -3 mV/m) signature from (2100 MLT, 19:40 UT) to (1730 MLT, 20:40 UT) is the westward-moving indentation that stripped off the outer edge of the plasmapause. From this linear signature we estimate the azimuthal speed of the undulation to be ≈−3.5 MLT/UT. The eastward-moving branch, from (0200 MLT, 19:20 UT) to (0800 MLT, 21 UT), is the signature of a subtler undulatory plasmapause motion, with a smaller plasmapause displacement (ripple) that propagated from 'I' to the dawnside at an azimuthal speed ≈3.6 MLT/UT. This eastward-propagating ripple is not an artifact of our analysis to infer E_π. The azimuthal flow speed at both dawn and dusk was $|\dot{\varphi}| \approx 0.9$ rad/hr, or $V_\varphi \approx 4\ R_E$/hr at $L = 4$. The peak E_π intensity near dusk (≈3 mV/m, dark red color) was about 1.7 times that of dawn (≈1.8, orange).

2.3. Substorm-Driven Convection

[11] From Figure 2a we see that the duskside undulation was part of a larger convection effect with a clear ripple signature on the plasmapause that propagated sunward from pre-midnight MLT. It is likely that this convection effect was primarily driven by a substorm onset (with associated dipolarization of the magnetotail). The SI13 camera of the IMAGE far ultraviolet (FUV) imager obtains global pictures of the electron aurora in 135.6-nm light [*Mende et al.*, 2000]. Figure 2b is a polar-projected auroral image from 19:05 UT, vs. magnetic latitude (Λ) and MLT. This FUV snapshot shows a substorm onset signature below 60°Λ and between 2100–2400 MLT, i.e., inside the wedge-shaped region bounded by the two thick yellow lines. The first evidence of this onset feature occurred at 19:00 UT (not shown). Recalling Figure 2a, it is remarkable that the onset feature occurred in the same MLT range, and at roughly the same time, as the first plasmapause indentation ('I') seen by EUV at 19:05 UT. This is strong circumstantial evidence that the substorm onset caused the convection enhancement responsible for the entire event, in which case this study contains the first global observations of the direct effects on the plasmapause of substorm-dipolarization-driven convection.

[12] We now discuss the possible role of dayside magnetopause reconnection (DMR) driven convection in the initiation of enhanced convection at 19:05 UT. From measurements of the interplanetary magnetic field (IMF) made by the ACE spacecraft [*Stone et al.*, 1998] (not shown), the IMF polarity at the dayside magnetopause changed to a strongly southward (−20 nT) orientation at about 18:30 UT. About 35 minutes later the initial plasmapause indentation occurred; this time delay is consistent with 20–30-minute magnetopause-to-plasmasphere delays observed by *Goldstein et al.* [2003a]. However, we speculate that DMR-driven convection played a minor role. The undulation occurred after 10 hours of stormtime enhanced convection, so that further increases in DMR-driven convection would have a minimal effect on the already eroded plasmasphere. As noted earlier, the net inward plasmapause displacement caused by the convection enhancement was small, inconsistent with typical DMR-driven nightside erosion, but perhaps consistent with the passage of a transient convective impulse that one might expect during a substorm dipolarization.

2.4. Sub-Auroral Polarization Stream

[13] The EUV observations of Figure 1 suggest qualitatively that the removal of the duskside bulge during the undulation was caused by a westward-moving flow such as a SAPS flow channel. In this section we present evidence of SAPS at the time and place of the undulation.

[14] Figure 3 displays ion drift meter data obtained during 4 successive passes ('A'–'D') of the Defense Meteorological Satellite Program (DMSP) F13 spacecraft [*Greenspan et al.*, 1986] through the duskside subauroral ionosphere (≈850 km altitude). Sunward flow speed V_X (km/s) is plotted vs. dipole L and magnetic latitude Λ along the DMSP F13 orbit. (Note: the 'sunward' flow is actually the inertial-frame velocity component perpendicular to the ~dawn-dusk F13 trajectory.) Each pass is labeled by start and stop UT (e.g., pass A was obtained between 18:20–18:23 UT), and the equatorward edge of the electron aurora (determined from DMSP particle data, not shown) is given by the filled circle.

[15] The flow profile of pass C (19:59–20:04 UT) contains a broad peak ($V_X > 1$ km/s), roughly 2L wide with a narrow 'spike' at the inner edge. This profile is typical of SAPS, although the broad peak does extend slightly above the auroral edge (the red circle). The four DMSP passes depict the birth and death of this SAPS feature, which apparently began to form after about 19:30 UT (later half of pass B), was fully-formed in pass C, and gone by 21:00 UT (pass D). The interval of SAPS activity (within 19:30–21:00 UT) is consistent with that of the undulation (19:36–20:37 UT). The L-range of enhanced flows also agrees with that of the undulation (L = 3–5, the gray shaded region in Figure 3). Earlier we inferred an azimuthal flow speed of

4 R_E/hr for the undulation. Mapping to 850 km using an $R^{3/2}$ velocity dependence (good for dipole B-field) yields ionospheric flow speed ≈1 km/s, in good agreement with the observed SAPS magnitude. Thus, duskside SAPS were seen by DMSP at the same time and place, and with the same intensity, as the flows associated with the removal of the duskside bulge during the undulation. We therefore assert that SAPS was responsible for removing the mild bulge that had formed before 19:36 UT.

[16] Enhanced sunward convection injects ring current plasma into the inner magnetosphere, producing pressure gradients that drive field-aligned currents (FAC) into the ionosphere to produce the SAPS [*Anderson et al.*, 2001; *Burke et al.*, 1998; *Foster and Burke*, 2002]. In this 17 April 2002 event, the primary source of the SAPS ring current ions seems to have been sunward convection resulting from the 19:00 UT substorm dipolarization that caused the initial plasmapause indentation ('I' in Figure 2a). But what caused the mild duskside bulge (Figure 1b) to form just prior to the SAPS? One possibility is that plasmaspheric plasma was removed from pre-midnight MLT and convected westward (i.e., sunward), and this redistribution of plasma created a mild bulge. A second possibility is that the enhanced post-dusk ring current pressure (from the injection) produced a local mild antisunward stretching of the geomagnetic field lines, and that cold, $E \times B$-drifting plasmaspheric plasma was thus pulled outward (R. W. Spiro, personal communication, 2004).

3. Conclusions

[17] In this letter we have reported IMAGE EUV observations of the duskside undulation of 17 April 2002, the first identification of this type of plasmapause motion. We used EUV-inferred electric field analysis to gain quantitative understanding of the dynamics and timing of this event. From its signature in E_π we estimated the undulatory ripple's azimuthal speed to be 4 R_E/hr (or 1 km/s in the ionosphere).

[18] We demonstrated that the 19:36–20:37 UT undulation was due to the presence of a SAPS flow channel observed by DMSP in the same range of MLT, L and UT as the undulation. The observed SAPS flows (1 km/s) are consistent with the EUV-observed undulation speed. The SAPS formed in response to a pre-midnight convection enhancement whose main cause was most likely a substorm onset. Thus, the 17 April EUV images contain the first global observations of some of the details of how both SAPS and substorm dipolarization affect the plasmasphere. A more comprehensive study of the interplay of the 17 April substorm, ring current, SAPS and plasmasphere will be reported in a future paper.

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