A plasmapause-like density boundary at high latitudes in Saturn's magnetosphere

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[1] Here we report the discovery of a well-defined plasma density boundary at high latitudes in Saturn's magnetosphere. The boundary separates a region of relatively high density at L less than about 8 to 15 from a region with densities nearly three orders of magnitude lower at higher L values. Magnetic field measurements show that strong field-aligned currents, probably associated with the aurora, are located just inside the boundary. Analyses of the anisotropy of energetic electrons show that the magnetic field lines are usually closed inside the boundary and open outside the boundary, although exceptions sometimes occur. The location of the boundary is also modulated at the ~10.6 to 10.8 hr rotational period of the planet. Many of these characteristics are similar to those predicted by Brice and Ioannidis for the plasmapause at a strongly magnetized, rapidly rotating planet such as Saturn.
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1. Introduction

[2] Earth's magnetosphere has a magnetic field-aligned boundary called the plasmapause, see Figure 1a, that separates a cold dense co-rotating plasma in the inner magnetosphere from a hot tenuous plasma that flows sunward through the outer magnetosphere [*Kivelson and Russell*, 1995]. The sunward flow is caused by the dayside merging of Earth's magnetic field with the solar wind magnetic field. The solar wind carries the merged magnetic field lines over the polar caps into the magnetotail where they reconnect and flow sunward on closed field lines. The sunward flow is driven by a cross-tail electric field that is controlled by the dayside merging rate. This circulation is called the Dungey cycle, after *Dungey* [1961].

[3] In an early paper on Jupiter's magnetosphere, *Brice and Ioannidis* [1970] made a quantitative prediction of the location of the plasmapause at Jupiter. Because Jupiter has a very strong magnetic field and is rapidly rotating, they predicted that Jupiter's magnetosphere would be dominated by a co-rotational electric field that is much stronger than the cross-tail electric field. Consequently, the plasmapause, if it existed at all, would be located near the outer boundary of the magnetosphere, see Figure 1b. Indeed, subsequent spacecraft measurements at Jupiter revealed a very large disk-like magnetosphere that is dominated by co-rotation [*Smith et al.*, 1974; *Bridge et al.*, 1979; *Krupp et al.*, 2001]. In this paper we report the discovery of a plasmapause-like boundary at high latitudes in Saturn's magnetosphere with properties similar to those predicted by *Brice and Ioannidis* for a rapidly rotating, strongly magnetized planet.

2. Evidence of a Plasmapause-Like Boundary

[4] The first hint of a plasmapause-like boundary at Saturn came from observations of auroral hiss. Auroral hiss is a whistler-mode emission commonly observed at high latitudes in Earth's auroral zones. This emission has also been observed in Saturn's magnetosphere by the Cassini Radio and Plasma Wave Science (RPWS) instrument [*Gurnett et al.*, 2009] and has been shown to be generated by field-aligned electron beams [*Kopf et al.*, 2010], very similar to the generation of auroral hiss at Earth. Auroral hiss often has a sharp upper cutoff frequency at the electron plasma frequency. Since the plasma frequency is controlled by the electron density, this cutoff can be used to measure the local electron density [*Persoon et al.*, 1988]. The electron plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}.

[5] An example of Saturnian auroral hiss with an upper cutoff near the electron plasma frequency is shown in Figure 2 (top). As can be seen the cutoff has an abrupt upward step at an L value of 11.4 and latitude of 50.8°. Here we define L as the equatorial radius (in Saturn radii, R_S) of the magnetic field line of a planet-centered spin-aligned dipole. Because of the relationship to the plasma frequency, we suspected that the upward step in the cutoff frequency would correspond to an upward step in the electron density. Indeed, as shown in Figure 2 (bottom), data from the Langmuir probe, which is also part of the RPWS instrument, show a corresponding abrupt upward step in the electron density. For a discussion of the techniques and limitations of the Langmuir probe, see *Wahlund et al.* [2005] and *Morooka et al.* [2009]. Note that the higher densities are located on the equatorward side of the step.

[6] In Earth's magnetosphere there are only two boundaries that have comparably sharp jumps in the plasma density: the magnetopause and the plasmapause. Since the radial distance

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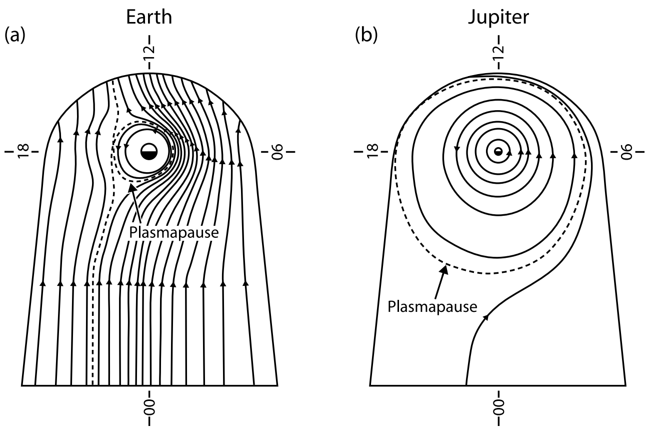

Figure 1. An illustration adapted from *Brice and Ioannidis* [1970] showing their comparison of the relative sizes of the plasmapause in the equatorial plane at (a) Earth and (b) Jupiter.

of the density jump in Figure 2 is only 4.6 R_S, the discontinuity cannot be the magnetopause, which at Saturn is typically located at 20 R_S, or more. Also, observationally the density jump looks very similar to the density jump observed during high-latitude passes through Earth's plasmapause [*Laakso et al.*, 2002]. Based on these simple considerations, we are led to the possibility that it is a plasmapause-like boundary. We note that the boundary is at a much higher L value than Earth's plasmapause, which is typically at L ~ 3 to 5 [*Kivelson and Russell*, 1995]. However, the higher L value is qualitatively consistent with the predictions of *Brice and Ioannidis*' model. Although their model is for Jupiter, Saturn also rotates rapidly and is strongly magnetized [*Smith et al.*, 1974], so the plasmapause should be located at a much higher L value than at Earth.

3. Region of Occurrence and Comparison to Other Observations

[7] Large abrupt steps in the electron density, similar to Figure 2, are a persistent feature of all of the Cassini high-latitude passes through Saturn's magnetosphere. Two intervals occur where the spacecraft orbit extended to high latitudes. The first was from about August 2006 to May 2007, and the second was from about January 2008 to August 2009. Of these, the second interval, which has nearly symmetrical north-to-south passes through the inner region, provides the most revealing observations.

[8] Typically, in these passes, a single upward step in the density occurs during the inbound pass, and a comparable downward step occurs during the outbound pass. An orbit that illustrates these features is shown in Figure 3. Figures 3 (top) and 3 (top middle) are in the same format as Figure 2. Figure 3 (bottom middle) shows the magnetic field from the magnetometer (MAG) [*Dougherty et al.*, 2004], and Figure 3 (bottom) shows the energetic electron flux from the MIMI-LEMMS instrument [*Krimigis et al.*, 2004]. The black vertical dashed lines mark the two major steps in the electron density, the first being an upward step at L = 12.0 during the inbound pass, and the second being a downward step at L = 14.6 during the outbound pass. Note that the local times of the two density steps are quite different, approximately 21.4 hr for the inbound pass and 0.3 hr for the outbound pass. Because of orbital considerations all of the high-latitude passes that we studied are confined to roughly these same local times.

[9] The magnetic data in the third panel show that large magnetic field disturbances occur in the region immediately inside the density boundary. The components ΔB_r, ΔB_θ, and ΔB_φ are the differences between the measured magnetic field and the magnetic field given by *Connerney et al.*'s [1982] magnetic field model. The magnetic field components are given in a right-hand (r, θ, φ) polar coordinate system. The largest magnetic field perturbations are seen to be in the B_φ component, as one would expect from a system of field-aligned currents similar to the current systems discussed by *Provan et al.* [2009] and *Talboys et al.* [2009]. Particularly large perturbations are evident in the B_φ component at about 01:45 UT and at about 09:35 UT. It is easily verified that these large disturbances are due to field-aligned currents directed upward away from the planet. Such upward directed currents are believed to be responsible for Saturn's aurora [*Cowley et al.*, 2008].

[10] An important question that arises is how the density boundary is related to the boundary between "closed" and "open" magnetic field lines. This question can be investigated by examining the anisotropy of energetic electrons. The bottom panel of Figure 3 shows the intensities in channels C5 and E0 of two LEMMS telescopes oriented such that they respond to ~200 keV electrons moving in opposite directions along the magnetic field. The black line, which is for C5, shows the intensity of electrons moving upward along the magnetic field; and the red line, which is for E0, shows the intensity of electrons moving downward. As can be seen, the

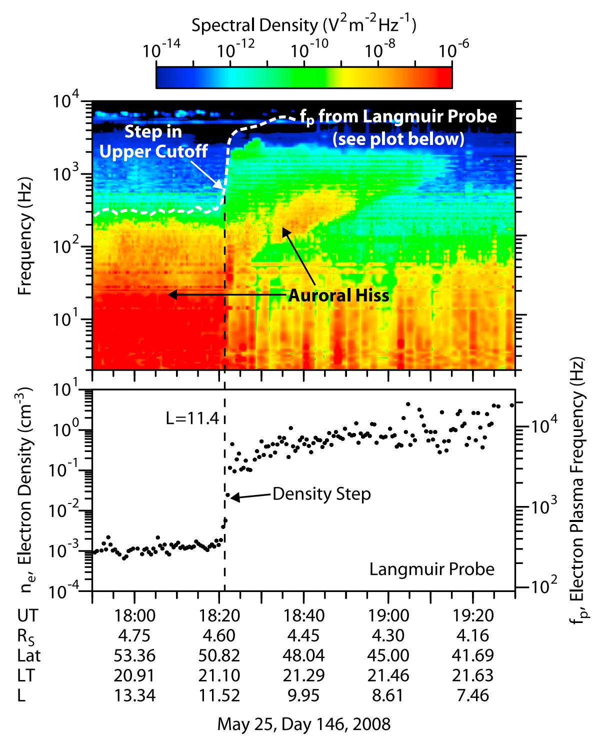

Figure 2. (top) The electric field spectrum of whistler-mode auroral hiss often has an abrupt step in the upper cutoff frequency. (bottom) This cutoff arises because of an abrupt upward step in the electron density.

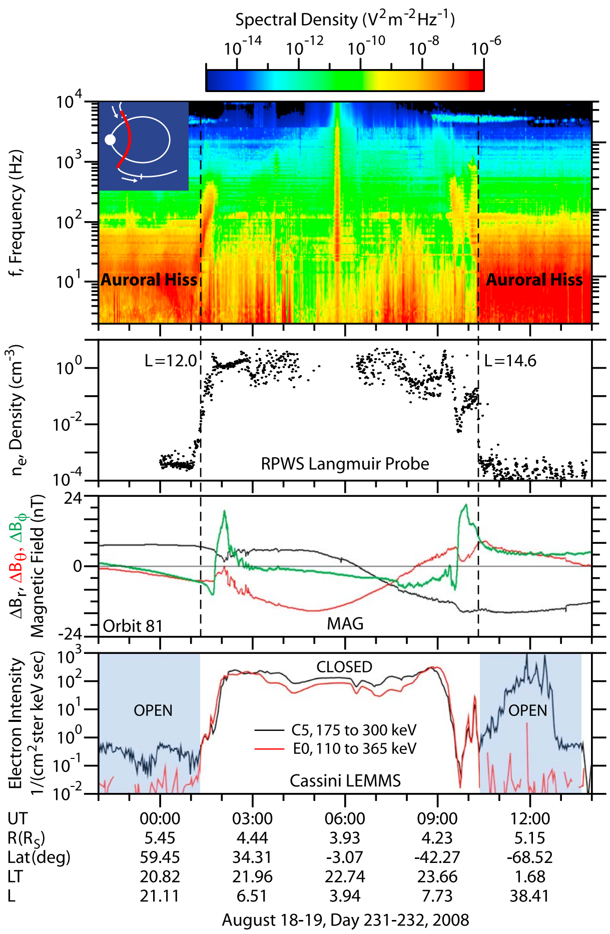

Figure 3. A multi-plot comparison of (top) the electric field spectrum of auroral hiss, (top middle) the electron density from the Langmuir probe, (bottom middle) three magnetic field components from the magnetometer (MAG), and (bottom) the electron flux from the MIMI-LEMMS energetic electron detector. A sketch of the spacecraft trajectory is shown in the upper left corner of Figure 3 (top).

intensities are almost the same in the region between the L = 12.0 and L = 14.6 density boundaries, which indicate a magnetically trapped population, i.e., closed magnetic field lines. However, in the region before the boundary at L = 12.0, and in the region after the boundary at L = 14.6, the upward intensities are substantially greater than the downward intensities. This means that no particles are returning from magnetic mirror points in the opposite hemisphere, so these field lines are open. In this case, the boundary between open and closed magnetic field lines is essentially coincident with the density boundary.

[11] At present we have carried out a detailed analysis of about a dozen passes similar to the one shown in Figure 3. Additional examples are given in the auxiliary material.[1] Many of these passes (similar to Figure S1 in the auxiliary material) follow the same basic pattern shown in Figure 3, consisting of (1) a single upward density step during the inbound pass followed by a single downward density step during the outbound pass; (2) strong field-aligned currents just inside the high density region; and (3) open field lines just outside the region of higher density. However, there are exceptions. Sometimes, the density boundary is poorly defined, as for the inbound pass in Figure S2, or may have a separate region of enhanced plasma density beyond the main density boundary, as during the inbound pass in Figure S3. In some cases the open/closed field line boundary is difficult to determine, either due to light contamination in one of the LEMMS telescopes, as for the inbound pass in Figure S1, or due to a gradual poorly defined transition, as in Figure S2. Although the open/closed field line boundary is usually coincident with the density boundary, exceptions do occur, as in Figure S3, where two well-defined closed field regions occur beyond the main density boundary.

4. Rotational Modulation

[12] For symmetrical north-to-south passes, such as in Figure 3, there is seldom evidence of multiple crossings that would indicate a rotational modulation. This is because the motion across the L shells during these north-south passes is very rapid, so rapid that there is little chance of detecting multiple crossings. However, during the first period of high-latitude passes (August 2006 to May 2007) there are many passes that clearly show rotational modulation effects. This is because the orbit during this period was such that the spacecraft tended to follow an L shell for several days, thereby revealing the ~10.6 to 10.8 hr rotational modulation.

[13] A good example of rotational modulation is shown in Figure 4, which has the same format as Figure 3, but for a longer time span. A clearly defined rotational modulation is evident in all four panels. The first crossing of the density boundary occurs at Day 337.62, where a sharp downward step occurs in the density. The MAG data shows that this density step is preceded by field-aligned currents, very similar to Figure 3. The energetic electron intensities in the bottom panel clearly show that the spacecraft is on closed field lines before the downward density step, and probably on open field lines after the density step. We say probably, because during this time detector C5 has light contamination and we cannot confirm that the intensity in C5 is substantially greater than in E0. However, the E0 intensities are at background levels, consistent with being on open field lines. A few hours later, at Day 337.88, an upward step occurs in the density, with a definite switch to closed field lines. This basic pattern then continues with decreasing amplitudes for the next day or so as the spacecraft moves to higher L values.

5. Conclusion

[14] Motivated by *Brice and Ioannidis* [1970], and the observational similarity to the Earth's plasmapause at high latitudes, we have referred to the high-latitude density step in Saturn's magnetosphere as a plasmapause-like boundary. At both planets the boundary separates a relatively cold dense inner region from a region of much lower density at higher L values. At Earth the plasma in the inner region originates from the ionosphere, whereas at Saturn the plasma originates primarily from Saturn's moon Enceladus. In both cases, the very low densities in the outer regions are due to the loss of plasma to the solar wind. At Earth this plasma loss is due to

[1] Auxiliary materials are available in the HTML. doi:10.1029/2010GL044466.

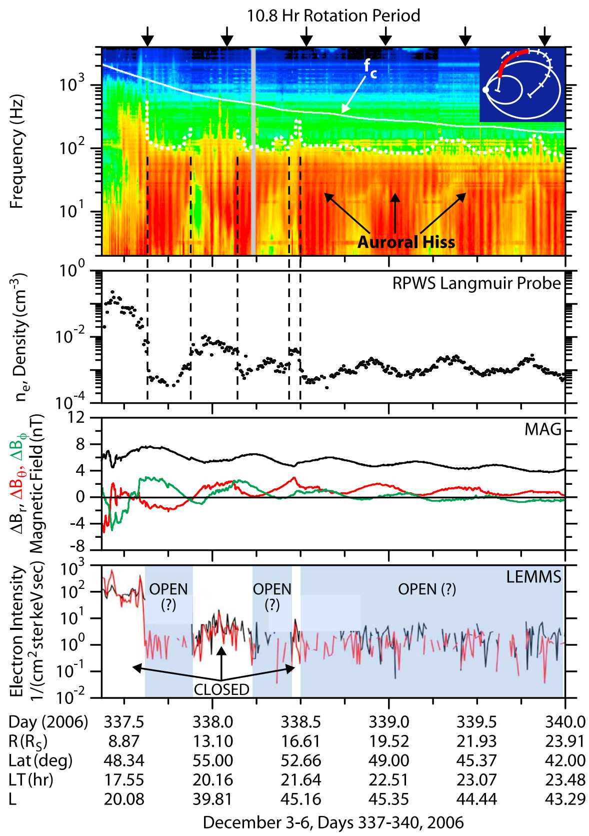

Figure 4. An outbound high-latitude pass on Days 337 to 340, 2006, in a format similar to Figure 3. During this pass the electron density, as well as the other parameters, show a very clear modulation at the ~10.6 to 10.8 hr rotation period of the planet.

the sunward plasma flow on closed field lines in the region between the plasmapause and the open/closed field line boundary (i.e., the Dungey cycle). At Saturn, based on the Brice and Ioannidis model, the expectation is that the plasma would also be lost to the solar wind via the Dungey cycle. Recently *McAndrews et al.* [2008] have reported evidence of dayside magnetic field merging which, if true, would require a region of sunward flow on closed magnetic field lines to satisfy magnetic flux conservation. However, in most of the cases that we have studied the density boundary is usually coincident with the open/closed field line boundary, which leaves little or no room for a region of sunward flow. However, there are exceptions, as in Figure S3, where a well-defined closed field region is observed beyond the main density step, which would allow for a region of sunward flow on closed field lines. However, such cases are not common. Clearly, further study is needed, especially at other local times and with the Cassini plasma instrument, to determine the extent to which a significant region of sunward flow exists on closed field lines.

[15] Although there are similarities to Earth's plasmapause, there are also significant differences. In a previous study of the electron density at Saturn by *Morooka et al.* [2009] no evidence was reported of a comparably sharp density boundary near the equatorial plane. At Earth a sharply defined plasmapause is commonly observed near the equator. This difference is likely due to the dominant role that centrifugal forces play in Saturn's magnetosphere, which at large distances distorts the magnetic field into a disk-like configuration near the equatorial plane [*Smith et al.*, 1974]. Because of this distortion the sharp boundary observed at high latitudes is almost certainly broadened near the equator due to the divergence of the magnetic field lines. This divergence, together with the rotational modulation and temporal variations that dominate at large radial distances, makes it very difficult to trace the boundary into the outer magnetosphere. Most likely it corresponds to the outer boundary of the plasma disk/plasma sheet.

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