The rotation of the plasmapause-like boundary at high latitudes in Saturn's magnetosphere and its relation to the eccentric rotation of the northern and southern auroral ovals

D. A. Gurnett,[1] A. M. Persoon,[1] J. B. Groene,[1] W. S. Kurth,[1] M. Morooka,[2] J.-E. Wahlund,[2] and J. D. Nichols[3]

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[1] Here we present a study of the rotation of the plasmapause-like density boundary discovered by the Cassini spacecraft at high latitudes in the Saturnian magnetosphere, and compare the results with previously published studies of high-latitude magnetic field perturbations and the eccentric rotation of the auroral ovals. Near the planet the density boundary is located at dipole L values ranging from about 8 to 15, and separates a region of very low densities at high latitudes from a region of higher densities at lower latitudes. We show that the density boundary rotates at different rates in the northern and southern hemispheres, and that the periods are the same as the modulation periods of Saturn kilometric radiation in those hemispheres. We also show that the phase of rotation in a given hemisphere is closely correlated with the phase of the high-latitude magnetic field perturbations observed by Cassini in that hemisphere, and also with the phase of the eccentric rotation of the auroral oval observed by the Hubble Space Telescope. **Citation:** Gurnett, D. A., A. M. Persoon, J. B. Groene, W. S. Kurth, M. Morooka, J.-E. Wahlund, and J. D. Nichols (2011), The rotation of the plasmapause-like boundary at high latitudes in Saturn's magnetosphere and its relation to the eccentric rotation of the northern and southern auroral ovals, *Geophys. Res. Lett.*, *38*, L21203, doi:10.1029/2011GL049547.

1. Introduction

[2] For over thirty years it has been known that Saturn's magnetosphere displays various periodicities that are driven by the rotation of the planet, even though its magnetic axis is aligned almost exactly with its rotational axis [*Connerney et al.*, 1982]. One of the most widely studied of these is Saturn Kilometric Radiation (SKR) which is an intense radio emission at kilometer-wavelengths discovered during the Voyager flybys of Saturn in 1980–1981 [*Kaiser et al.*, 1980]. It is now known that the SKR rotational modulation period is not only variable, but has two periods [*Kurth et al.*, 2008], one at about 10.6 hr that originates primarily from a source in the northern auroral region, and the other at about 10.8 hr that originates primarily from a source in the southern auroral region [*Gurnett et al.*, 2009a]. Recent Cassini data show that these two periods reversed a few months after the August 2009 equinox [*Gurnett et al.*, 2010a; *Lamy*, 2011].

[3] Although various particle and field observations in Saturn's magnetosphere showed periods similar to the SKR modulation [*Espinosa and Dougherty*, 2000; *Carbary et al.*, 2007; *Morooka et al.*, 2009], it was only recently that the northern and southern SKR periods have been identified in other data. In particular, *Andrews et al.* [2010] showed that the north and south SKR periods correspond to the rotation periods of quasi-dipolar magnetic field perturbations observed at high latitudes over the northern and southern polar regions, and *Nichols et al.* [2010] showed that the two SKR periods are the same as the periods of dawn-dusk oscillations of the northern and southern auroral ovals as viewed by the Hubble Space Telescope (HST). The dawn-dusk oscillations were interpreted as being due to the eccentric rotation of the auroral ovals with amplitudes of about 1 to 2 degrees. In this paper we present a study of the rotation of the plasmapause-like density boundary discovered at high latitudes by *Gurnett et al.* [2010b]. We will show that the density boundary rotates at different rates in the two hemispheres, and that the rotation period in a given hemisphere is the same as the SKR period in that hemisphere. These results have important implications for the relationship of the density boundary to magnetic field perturbations observed in the northern and southern hemispheres, and to the eccentric rotation of Saturn's auroral ovals.

2. The Plasmapause-Like Density Boundary and Its Rotation

[4] Electron density measurements from the Langmuir probe on Cassini show that a well-defined rotating density boundary exists at high latitudes in Saturn's magnetosphere [*Gurnett et al.*, 2010b]. The boundary is observationally very similar to Earth's plasmapause, and separates a region of very low densities, $\sim 10^{-4}$ to 10^{-3} cm^{-3}, at high latitudes from a region of much higher densities, 10^{-2} to 10^{0} cm^{-3}, at lower latitudes. Near the planet the boundary is typically located at dipole L values from about 8 to 15, although at greater radial distances larger L values are often observed, probably due to the distorting effects of magnetospheric currents. Anisotropy measurements from the Cassini MIMI-LEMMS instrument show that the density boundary is located near the boundary between "open" and "closed" magnetic field lines, see *Gurnett et al.* [2010b]. The close relationship to the open/closed field line boundary strongly suggests that the density boundary is aligned with the magnetic field. Comparisons with Cassini magnetic field measurements show that the boundary is located a few degrees poleward of the region of

[1]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.
[2]Swedish Institute of Space Physics, Uppsala, Sweden.
[3]Department of Physics and Astronomy, University of Leicester, Leicester, UK.

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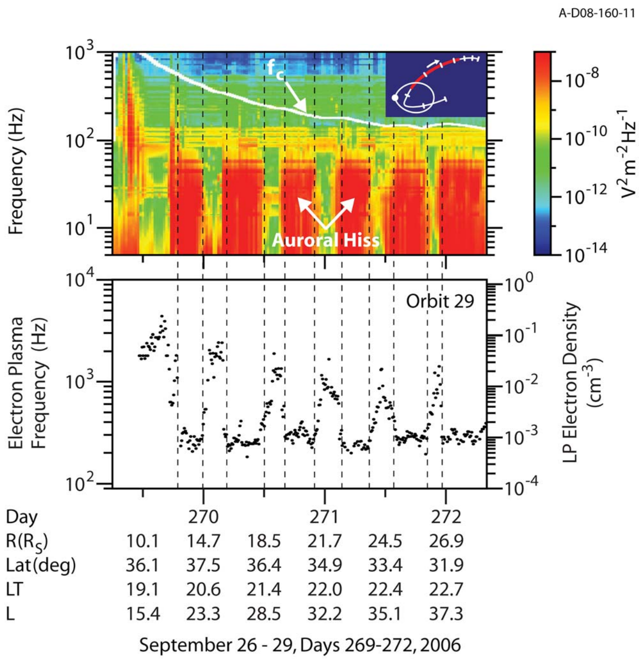

Figure 1. (top) The electric field spectrum of auroral hiss detected by the Cassini RPWS instrument, and (bottom) the electron density measured by the RPWS Langmuir probe for an outbound high-latitude pass. See *Gurnett et al.* [2004] for a description of the RPWS instrument.

upward field-aligned currents that are believed to be responsible for Saturn's aurora [*Bunce et al.*, 2010].

[5] On certain orbits where the spacecraft moves nearly parallel to the high latitude magnetic field lines, a well-defined square-wave-like density modulation can often be seen in the electron density with a period comparable to the rotation period of the planet. A good example of this density modulation is given in Figure 1 (bottom), which shows the electron density alternating between a low value of about 1 to 2×10^{-3} cm^{-3}, and a higher value of about 10^{-2} to 10^{-1} cm^{-3}. A similar square-wave-like modulation can also be seen in Figure 1 (top) which shows the electric field intensity of auroral hiss. Auroral hiss is a whistler-mode emission that is commonly observed in Saturn's magnetosphere, and has been shown to be anti-correlated with the plasma density [*Gurnett et al.*, 2009b]. When the Langmuir probe data are noisy or irregular, the auroral hiss sometimes provides a useful confirmation of the density boundary.

3. Rotational Phase and Shape of the Density Structure

[6] Two periods occur in the Cassini data that provide measurements at sufficiently high latitudes, $|\mathrm{Lat}| > 30°$, to study the rotating plasma density structure. The first is from about day 269, 2006, to day 162, 2007, and the second is from about day 60, 2008 to day 230, 2009. For this study we analyzed seven consecutive passes from the first period, and thirteen consecutive passes from the second period, all of which had recognizable square-wave-like density and auroral hiss waveforms. During the first period the orbit is such that for the outbound northern hemisphere passes, the spacecraft often skims along the high latitude L-shells for several days, thereby revealing a very clear density modulation, as in Figure 1. Unfortunately, during this period the inbound southern high latitude passes tend to be very short, usually less than one day, often too short to even identify the density modulation. Consequently, very few measurements can be made in the southern hemisphere during the first period. For the second period the orbit is more nearly symmetric with respect to the equatorial plane and good high latitude observations can be made in both hemispheres, often much closer to the planet, 5 R_S or less, although of shorter duration than for the first period. The second period has the advantage that it overlaps the period, day 23 to 66, 2009, when the HST auroral images were obtained, thereby providing a better comparison with *Nichols et al.* [2010].

[7] To measure the phase of the density modulation we used the SLS4 (north) and SLS4 (south) SKR longitude system described by *Gurnett et al.* [2011]. This system is based on a tracking filter that separately tracks the rotation rates of the northern and southern SKR components. To determine the phase of the density modulation we first identified the times of the upward and downward density steps, as indicated by the vertical black dashed lines in Figure 1. Once the locations of the density steps were identified, the spacecraft longitude, λ, of each density step was then computed, taking care to use the north longitude system for data from the northern hemisphere, and the south longitude system for data from the southern hemisphere. Using these measurements the longitude, $\overline{\lambda}$, at the center of the each high density region was calculated using $\overline{\lambda} = (1/2)\,(\lambda_u + \lambda_d)$, where "u" is the upward density step and "d" is the downward density step. The longitude at the center of each low density region was also calculated.

[8] Next we compare the rotational phases of the centers of the high and low density regions to the phase of the eccentric rotation of the auroral oval reported by *Nichols et al.* [2010]. Since the SKR has a nearly clock-like temporal dependence [*Andrews et al.*, 2011], the longitude of the Sun, λ_{Sun}, was used as the coordinate system for the SKR phase. By our convention the reference longitude, $\lambda_{Sun} = 0$, is taken to be the time of maximum SKR intensity. Since the density measurements involve the longitude of the spacecraft, λ, we must be able to transform between the two longitude systems. It is easy to show that the two systems are linked by the equation $\lambda = \lambda_{Sun} + [12 - \mathrm{LT}]\cdot 15°$, where LT is the local time of the spacecraft and the longitudes are in degrees. *Nichols et al.* [2010] showed that the phase of the eccentric rotation of the auroral oval is directed toward the Sun at the time of maximum SKR intensity, i.e., when $\lambda_{Sun} = 0$. Therefore, if we set $\lambda_{Sun} = 0$ in the above equation, we can compute the local time of the center of the high density region at the time when the SKR is at maximum intensity (i.e., when the auroral oval is shifted toward the Sun). The resulting equation is $\mathrm{LT} = 12 - (\overline{\lambda}/15°)$. Note that this step involves propagating the $\overline{\lambda}$ measurement forward in time at the SKR rotation rate until the $\lambda_{Sun} = 0$ condition is met. The resulting local times are shown by the red and blue arrows in Figure 2, using all of the available measurements, with one arrow per rotation. The red arrows show the local times for the centers of the high density regions, and the blue arrows show the local times for the centers of the low density regions. The view is from the north, with the Sun upward, along the + x axis. The panels on the left are from the first period of high latitude observations (orbits 29–35), and the panels on the right are from the second period

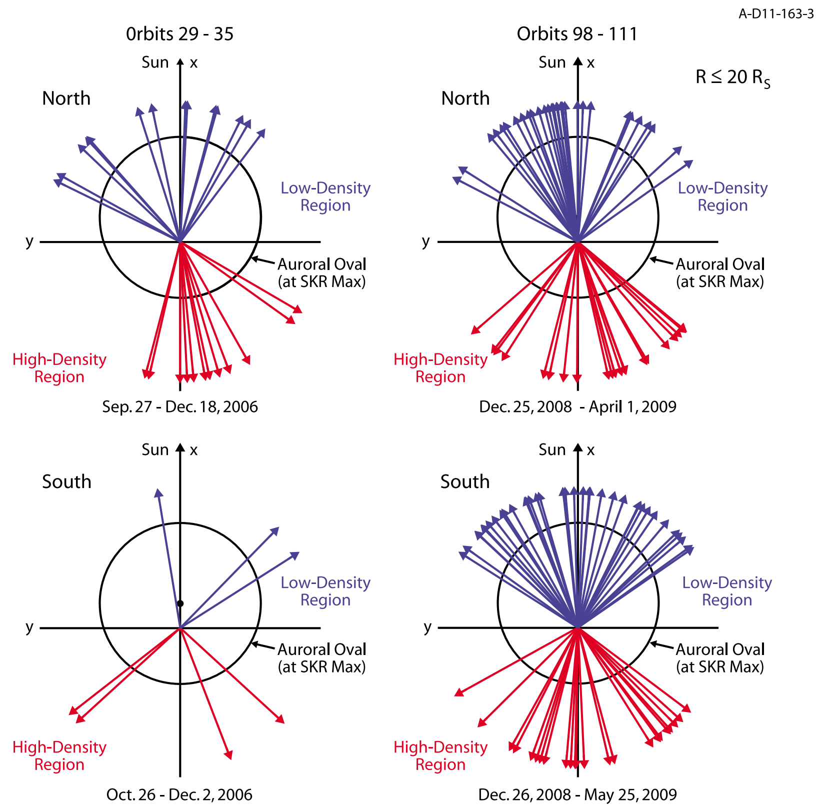

Figure 2. The red and blue arrows show the local times of the centers of the high and low density regions for each rotation where measurements are available, propagated forward to the time of maximum SKR intensity ($\lambda_{Sun} = 0$) in that hemisphere.

of high latitude observations (orbits 98–111). The top row is for the northern hemisphere, and the bottom row is for the southern hemisphere. With the exception of the southern hemisphere observations during orbits 29–35 (lower left panel), for which there are very few measurements, the results are very consistent and show that the density boundary rotates at the corresponding SKR rate in each hemisphere. For a further discussion of this result see the auxiliary material.[1] Figure 2 also shows that at the time of maximum SKR intensity (i.e., $\lambda_{Sun} = 0$), the centers of the high and low density regions are shifted away and toward the Sun, respectively.

[9] Using the above measurements it is also possible to obtain information about the shape of the rotating density structure. It is obvious in Figure 2 that there is considerable scatter in the phase of the rotation (i.e., the directions of the red and blue arrows). Since the SLS4 longitude system varies smoothly on time scales of weeks to months, this scatter shows that the plasma rotation has large short-term phase fluctuations, sometimes as large as ±60°. Similar short-term phase fluctuations have also been noted in the SKR and magnetic field data [*Zarka et al.*, 2007; *Andrews et al.*, 2008]. To remove this phase jitter and reveal the basic shape of the rotating structure, for each rotation we subtracted the longitude of the center of the high density region from the longitude of the spacecraft, $\Delta\lambda = \lambda - \overline{\lambda}$, and plotted $\Delta\lambda$ versus invariant latitude $\Lambda = \cos^{-1}(1/\sqrt{L})$ for all of the measurements in the high density region. Invariant latitude is useful

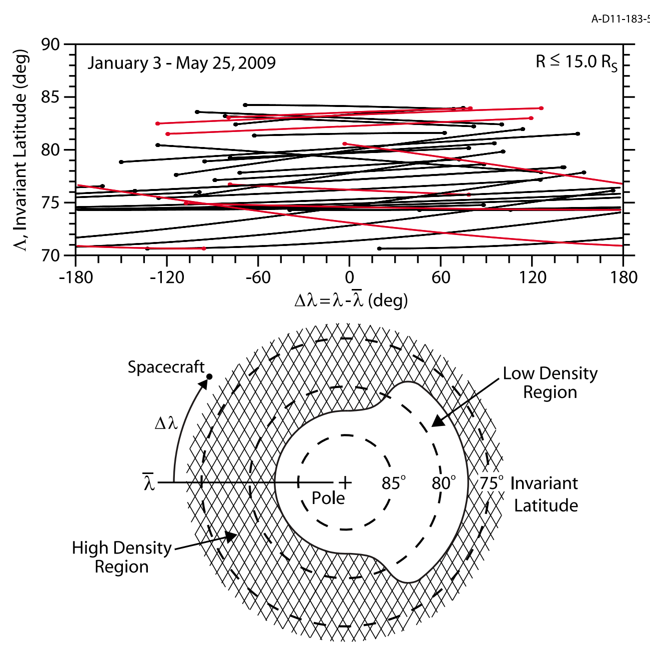

Figure 3. (top) The lines show the spacecraft trajectory in the high density region as a function of $\Delta\lambda = \lambda - \overline{\lambda}$ and invariant latitude, Λ. The black lines are for the northern hemisphere and the red lines are for the southern hemisphere. (bottom) The sketch shows a polar view of the inferred shape of the density boundary in this rotating density-centered coordinate system.

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL049547.

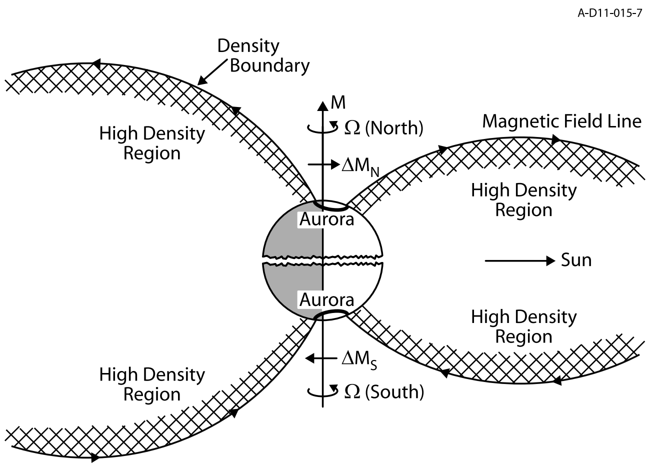

Figure 4. The geometric relationship between the rotating plasma, the magnetic field, and the auroral oval at a specific time, when the SKR is at maximum intensity in both hemispheres. As time evolves from this condition, the two patterns drift in relative phase because the magnetospheric rotation rates, Ω (North) and Ω (South) are different in the two hemispheres.

here because it maps the magnetic field line to the surface of the planet, thereby providing a comparison with the location of the auroral oval. The resulting plot is shown in Figure 3 (top). As can be seen, the ($\Delta\lambda$, Λ) coordinate system does a good job organizing the data. At higher latitudes, greater than about 80°, the high density region (solid lines) mainly occurs in the range from about $\Delta\lambda = -100°$ to +100°. Note that that the boundaries of the high density region are rather abrupt, with the region of high densities tending to expand poleward from about $\Delta\lambda \approx -120°$ to −90°, and contract equatorward from about $\Delta\lambda \approx +90°$ to +120°. This implies that the high density region has rather abrupt cam-shaped rotational transitions, as illustrated in Figure 3 (bottom). Note also that the boundary of the high density region is generally poleward of the auroral oval, which at Saturn is typically in the range from about 74° to 76° [*Badman et al.*, 2006]. This is consistent with the results of *Gurnett et al.* [2010b] who found that the density boundary is usually poleward of the upward field-aligned currents associated with the aurora.

4. Summary

[10] We have analyzed the rotation of the plasmapause-like density boundary discovered by Cassini at high latitudes in Saturn's magnetosphere. The boundary is found to rotate at different rates in the northern and southern hemispheres, with a rotation period that matches the SKR period in those hemispheres. The rotational phase is such that when the SKR is at maximum intensity in a given hemisphere the low density region is shifted (tilted) toward the Sun, as illustrated in Figure 4. At this same phase, *Nichols et al.* [2010] showed that the rotation of the center of the auroral oval is such that the oval is shifted (tilted) toward the Sun, and that the dipole moment, $\Delta\mathbf{M}$, of the high latitude magnetic field perturbations is directed toward the Sun in the northern hemisphere, and away from the Sun in the southern hemisphere. The corresponding geometries of the auroral ovals, and the magnetic field in the two hemispheres, are also shown in Figure 4, all with somewhat exaggerated tilts. It is important to note that this sketch is a snapshot at a specific time, i.e., when the SKR is at maximum intensity in both hemispheres. As time advances from this condition, the auroral oval, the magnetic field, and the plasma rotate synchronously in a given hemisphere, but at different rates in the north and south. Just what drives these two different magnetospheric rotations is a major scientific question that remains to be answered.

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J. B. Groene, D. A. Gurnett, W. S. Kurth, and A. M. Persoon, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA.

M. Morooka and J.-E. Wahlund, Swedish Institute of Space Physics, Box 537 SE-751 21, Uppsala, Sweden.

J. D. Nichols, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK.