JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 111, A06214, doi:10.1029/2005JA011432, 2006

Whistler-mode auroral hiss emissions observed near Saturn's B ring

L. Xin,[1] D. A. Gurnett,[1] O. Santolík,[1,2] W. S. Kurth,[1] and G. B. Hospodarsky[1]

Received 16 September 2005; revised 8 December 2005; accepted 15 February 2006; published 22 June 2006.

[1] An unusual whistler-mode emission, similar to terrestrial auroral hiss, was observed by the radio and plasma wave instrument on the Cassini spacecraft during the 1 July 2004 pass over the rings of Saturn. By using an electron density model that is consistent with measurements of the local electron plasma frequency, ray-tracing calculations have been performed to determine the source of the emission. The calculations assume that the emission is propagating near the whistler-mode resonance cone. It is found that the best fit to the V-shaped lower cutoff of the emission is obtained if the source is located very close to the B ring at a distance of about 1.76 R_S from the center of Saturn. On the basis of the close similarity to terrestrial auroral hiss we suggest that the emission is produced by a magnetic field-aligned beam of electrons that is directed outward away from the ring. The electron beam is most likely accelerated by parallel electric fields that arise as part of a current system induced by the interaction of the ring with the corotating magnetosphere of Saturn.

Citation: Xin, L., D. A. Gurnett, O. Santolík, W. S. Kurth, and G. B. Hospodarsky (2006), Whistler-mode auroral hiss emissions observed near Saturn's B ring, *J. Geophys. Res.*, *111*, A06214, doi:10.1029/2005JA011432.

1. Introduction

[2] On 1 July 2004, the Cassini spacecraft made a close pass over the rings of Saturn. During the outbound portion of the pass, the Radio and Plasma Wave Science (RPWS) instrument detected an electric field emission that has spectral characteristics very similar to a type of whistler-mode emission called auroral hiss that is commonly observed over Earth's auroral zones [*Gurnett et al.*, 2005]. This paper gives a detailed analysis of the "auroral hiss" observed over Saturn's rings. For a description of the Cassini mission see *Matson et al.* [2002], and for a description of the RPWS instrument see *Gurnett et al.* [2004].

[3] A frequency-time spectrum of the auroral hiss observed over Saturn's rings is shown in Figure 1. As can be seen, the emission has a V-shaped low-frequency cutoff that gives the emission a characteristic funnel shape very similar to the spectrum of terrestrial auroral hiss [*Gurnett*, 1966]. Auroral hiss-like emissions with this characteristic funnel shape have also been detected by the Voyager and Galileo spacecraft near Jupiter's moon Io and in the vicinity of the Io plasma torus [*Gurnett et al.*, 1979; *Morgan et al.*, 1994; *Xin et al.*, 2006]. In all of these cases the emissions are known to be propagating in the whistler mode, since the frequency is always above the local proton cyclotron frequency and below the electron plasma frequency or electron cyclotron frequency, whichever is smaller. The whistler mode is the only plasma wave mode that can propagate in this frequency range [*Gurnett and Bhattacharjee*, 2005]. The V-shaped low-frequency cutoff of these emissions can be explained by whistler-mode propagation near the resonance cone, which is a cone of directions around the magnetic field where the index of refraction becomes very large [*Mosier and Gurnett*, 1969; *Gurnett et al.*, 1983; *Santolík and Gurnett*, 2002]. Near the resonance cone the whistler mode becomes quasi-electrostatic and the phase velocity becomes very small, much less than the speed of light. Early satellite measurements provided evidence that auroral hiss is produced by intense fluxes, 10^4 to 10^7 electrons cm^{-2} s^{-1}, of low-energy (hundred eV to several keV) electrons [*Gurnett*, 1966; *Gurnett and Frank*, 1972]. It is now commonly believed that auroral hiss is produced by an electron beam via the Landau resonance at $v_{\parallel} = \omega/k_{\parallel}$. This generation mechanism has been convincingly verified by remote observations of the whistler-mode radiation produced by an artificial electron beam ejected from an electron gun on the space shuttle [*Gurnett et al.*, 1986; *Farrell and Gurnett*, 1988].

[1]Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa, USA.

[2]Also at Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic.

0148-0227/06/2005JA011432$09.00

2. Observations

[4] Polar and equatorial views of the Cassini trajectory during the 1 July 2004 pass over the rings of Saturn are shown in Figure 2. The auroral hiss occurred during the outbound portion of the pass from about 0310 to 0345 Universal Time (UT). The radial distance from the center of the planet during this time varied from about 1.49 to 1.91 Saturn radii (R_S), and the latitude decreased slowly from about 13.5° to 6.6°. Because of high electric field noise levels from about 0112 to 0248 UT caused by the firing of the rocket motor during the Saturn orbital insertion, it was not possible to determine if a comparable type of emission

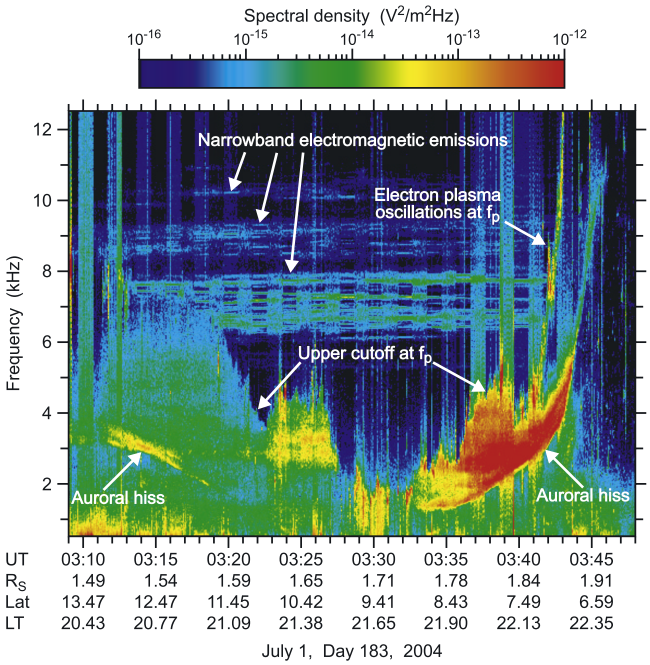

Figure 1. A frequency-time spectrogram showing the electric field intensities detected by the Cassini spacecraft during the first pass over Saturn's rings on 1 July 2004. The emission with the funnel-shaped low-frequency cutoff is believed to be similar to a terrestrial whistler-mode emission called auroral hiss.

occurred on the inbound pass. The funnel shape of the auroral hiss emission, with the characteristic V-shaped low-frequency cutoff, is clearly evident in Figure 1. The center of the funnel is located at about 0330 UT. As is often the case with terrestrial auroral hiss, the emission is quasi-electrostatic and was not detected with the RPWS magnetic antenna. The emission also has a sharply defined upper cutoff frequency. The frequency of the upper cutoff varies considerably, decreasing from about 8 kHz on the left side of the spectrogram, reaching a minimum of about 2 kHz near the center of the funnel, and then increasing to more than 12 kHz on the right side of the spectrogram where the funnel bends up sharply. The upper cutoff is believed to be at the local electron plasma frequency. It is well known from cold plasma theory [*Gurnett and Bhattacharjee*, 2005] that the upper frequency limit of the whistler mode is either at the electron plasma frequency, f_p, or the electron cyclotron frequency, f_c, whichever is lower. The electron plasma frequency is given by $f_p = 8980\sqrt{n_e}$ Hz, where the electron density, n_e, is in cm^{-3}, and the electron cyclotron frequency is given by $f_c = 28$ B Hz, where the magnetic field strength, B, is in nT. Since the electron cyclotron frequency in this region is about 100 kHz [*Gurnett et al.*, 2005], it is clear that the sharp upper cutoff cannot be at the electron cyclotron frequency, so we believe that it is at the electron plasma frequency. Since the electron plasma frequency depends only on the electron density, the upper cutoff provides a measurement of the local electron density. This technique for measuring the electron density has been previously used by *Persoon et al.* [1988] to provide measurements of electron densities over Earth's polar regions. For a further discussion of this technique, see *Santolík and Gurnett* [2002] and *Santolík et al.* [2005].

[5] At about 0341 UT a narrowband emission can be seen rising up out of the auroral hiss. This narrowband emission is also quasi-electrostatic, since it cannot be detected with the RPWS magnetic field sensor, and is believed to be due to electrostatic oscillations at the electron plasma frequency. The rapid rise in the frequency of the electron plasma oscillations from about 0342 to 0343 UT indicates that the electron density is increasing very rapidly in this region. From Figure 2 one can see that this rapid rise occurs as the spacecraft crosses over the Cassini division. A similar increase in the plasma density has been detected in this same region by the plasma instrument on Cassini [*Young et al.*, 2005]. The density increase most likely occurs because particles can pass freely through the ring in the Cassini division, thereby allowing the plasma to build up to higher densities.

3. Analysis

[6] Previous studies of terrestrial auroral hiss [*Mosier and Gurnett*, 1969; *Gurnett et al.*, 1983] have shown that the V-shaped low-frequency cutoff of auroral hiss can be explained by whistler-mode propagation near the resonance cone. In contrast to observations of auroral hiss at Earth,

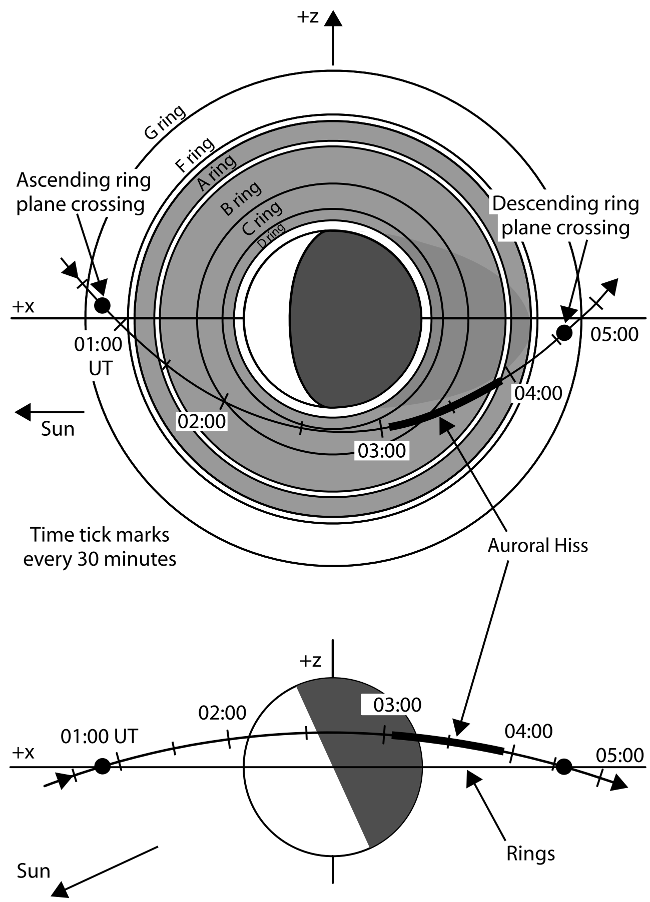

Figure 2. Polar and side views of the Cassini trajectory during the first pass through the Saturn system. The time range in which auroral hiss-like emissions were detected is labeled.

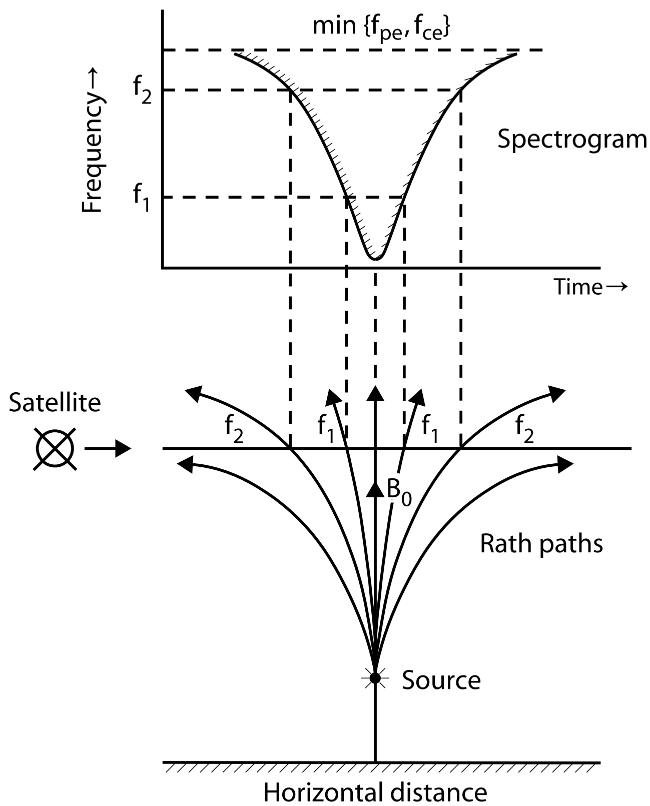

Figure 3. A plot showing how a funnel-shaped frequency-time spectrum is generated by whistler-mode waves propagating from a point source near the resonance cone.

where the electron plasma frequency is typically comparable to or greater than the electron cyclotron frequency, for the auroral hiss at Saturn the electron cyclotron frequency is much greater than the plasma frequency, i.e., $f_p \ll f_c$. Under these conditions it can be shown that the ray path direction, ψ_{res} relative to the magnetic field is given to a good approximation by the equation

$$\tan^2 \psi_{res} = -\frac{S}{P} \approx \frac{f^2}{f_p^2 - f^2}, \tag{1}$$

where f is the wave frequency, and S and P are functions defined by *Stix* [1992]. The above equation shows that higher frequencies propagate at larger angles with respect to the magnetic field. The resulting ray paths, shown in the bottom panel of Figure 3, then deviate to larger angles relative to the magnetic field line as the frequency increases. As the spacecraft approaches the magnetic field line through the source, the highest frequencies are observed first, followed by successively lower frequencies, thereby leading to the characteristic V-shaped low-frequency envelope. The qualitative shape of the low-frequency cutoff is as shown in the upper panel of Figure 3. It is obvious from equation (1) that the ray path directions, and therefore the frequency-time shape of the low-frequency cutoff, depend on the spatial variations of the plasma frequency, and hence on the electron density distribution. Conversely, one can also see that the shape of the low-frequency cutoff, which we know in this case, provides important constraints on the source position and the electron density distribution.

[7] One of our objectives in this analysis is to use ray tracing computations to put constraints on the source location. Since the ray path direction depends on the electron density (via the electron plasma frequency), we must develop a reasonable model for the electron density distribution. Fortunately, the electron plasma frequency, and hence the electron density, is known at the location of the spacecraft from the upper cutoff of the auroral hiss. Since the resulting electron density profile has considerable fine structure that is likely due to local fluctuations, our first step was to fit the electron density profile from 0309 to 0343 UT to a relatively smooth function that follows the large-scale variations. We do this by using a fourth-order polynomial and an exponential function that depend on the *McIlwain* [1961] magnetic field line parameter, L. For the magnetic field model we use a dipole aligned with Saturn's rotational axis. The L value is then simply the radial distance at which the magnetic field crosses the magnetic equator, measured in Saturn radii from the center of the planet. We found that the best fit equation for the electron density along the spacecraft trajectory is given by

$$\begin{aligned} n_0(L) = {} & a_4L^4 + a_3L^3 + a_2L^2 + a_1L + a_0 \\ & + A\exp[(L - L_0)/l_0]\mathrm{cm}^{-3} \end{aligned} \tag{2}$$

where $a_4 = 568.1$, $a_3 = -3931.9$, $a_2 = 10217.1$, $a_1 = -11815.6$, $a_0 = 5131.8$, $A = 0.1$, $L_0 = 1.905$, $l_0 = 0.005$, and L is in units of Saturn radii, R_S. The exponential term is used to account for the rapid rise in the electron density near the Cassini division. A comparison of the above fit with the measured electron density profile is shown in Figure 4.

[8] To provide a complete description of the electron density distribution, we must also specify how the electron density varies along the magnetic field, i.e., in regions not sampled by the spacecraft. To account for this dependence, we assume that the ion density, which ultimately controls the electron density via the charge neutrality condition, varies as a Gaussian function, $\exp(-s^2/H^2)$ of the distance, s, along the magnetic field line from the equatorial plane. The choice of a Gaussian function is motivated by the fact that for a rapidly rotating magnetosphere the centrifugal force causes the ion density to vary approximately as $\exp(-z^2/H^2)$, where z is the perpendicular distance from the equator and H is a characteristic scale length called the scale height [*Gledhill*, 1967; *Hill and Michel*, 1976]. Since near the equator the height z is almost the same as the distance s along the magnetic field line, we have substituted z = s in the Gaussian function. We assume that in the region near the rings there are three types of ions, H^+, O_2^+ and O^+ with relative contributions of 20%, 50%, and 30%, respectively [*Waite et al.*, 2005; *Young et al.*, 2005]. The electron density $n(\rho, z)$ is then given by the equation

$$\begin{aligned} n(L,s) = {} & \frac{n_0(L)}{\left[0.2\exp\left(-\frac{s_{traj}^2}{H_1^2}\right) + 0.5\exp\left(-\frac{s_{traj}^2}{H_2^2}\right) + 0.3\exp\left(-\frac{s_{traj}^2}{H_3^2}\right)\right]} \\ & \times \left[0.2\exp\left(-\frac{s^2}{H_1^2}\right) + 0.5\exp\left(-\frac{s^2}{H_2^2}\right) + 0.3\exp\left(-\frac{s^2}{H_3^2}\right)\right]\mathrm{cm}^{-3}, \end{aligned} \tag{3}$$

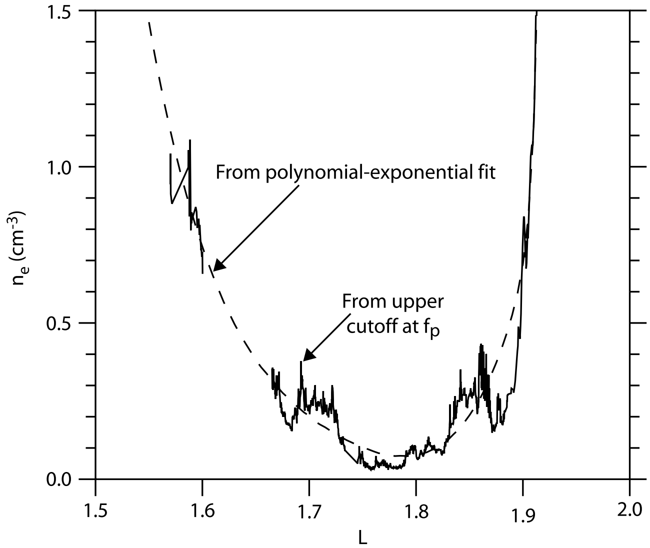

Figure 4. A smooth polynomial-exponential fit to the electron density measured from the upper cutoff of the auroral hiss.

where $n_0(L)$ is given by equation (2). The terms H_1, H_2, and H_3 represent the scale heights of the H^+, O_2^+, and O^+ ions, respectively. For a constant temperature these scale heights obey the simple relationships $H_1 = 4\sqrt{2}H_2 = 4H_3$. The quantity s_{traj} is a single-valued function of L and is determined by the Cassini trajectory. From equation (3) it can be seen that if (L, s) is located on the trajectory the two exponential summations cancel, leading to $n(L_{traj}, s_{traj}) = n_0(L_{traj})$, thereby recovering the electron density along the trajectory. In order to obtain a good fit to the low-frequency cutoff of the auroral hiss, we found that the scale height must vary as a function of the distance, ρ, which is the distance from Saturn's rotational axis. A scale height of $H_1 = 0.18$ gives a good fit to the left-hand branch of the low-frequency cutoff (from about 0309 to 0330 UT), but not the right-hand branch. Therefore we set the scale height to a constant, H_0, along the left-hand branch. To fit the right-hand branch, the scale height was modeled by the following equation

$$H_1 = H_0 + A\left[\tan^{-1}\left(\frac{\rho - \rho_0}{l}\right) + \frac{\pi}{2}\right], \quad (4)$$

where $H_0 = 0.20$, $A = \frac{1.4 - H_0}{\pi}$, $\rho_0 = 1.75$, and $l = 0.01$ were found to give the best overall fit. The scale heights H_2 and H_3 were calculated using $H_1 = 4\sqrt{2}H_2$ and $H_1 = 4H_3$.

[9] On the basis of the electron density model described above and a simple dipole magnetic field, a two-dimensional ray tracing analysis has been performed by carrying out a fourth-order Runge-Kutta integration of the ray tracing equations assuming resonance cone propagation. We found that the source position that gives the best fit is located almost exactly in the equatorial plane at $z = 0.0 \pm 0.02$ and a distance of $\rho = 1.76 \pm 0.04\ R_S$ from the center of Saturn. The resulting ray path trajectories are shown in Figure 5 plotted in (ρ, z) coordinates. The computed low-frequency cutoff is shown by the red line in Figure 6. The fit is quite good at frequencies up to 4 kHz. At higher frequencies, the computed cutoff does not follow the dramatic rise of the plasma frequency after about 0344 UT. This sudden rise in frequency can not be explained by the present model and is most likely due to some yet unknown aspect of the electron density distribution that is not adequately represented by our model. Careful inspection shows that this high-frequency emission is located very close to the inner edge of the Cassini division, which is at L = 1.95 R_S. The free passage of plasma through the ring plane in the Cassini division most likely causes major changes in the electron density that is not included in our model.

4. Discussion

[10] Since auroral hiss is known to be produced by an electron beam, an emission source at the equator implies

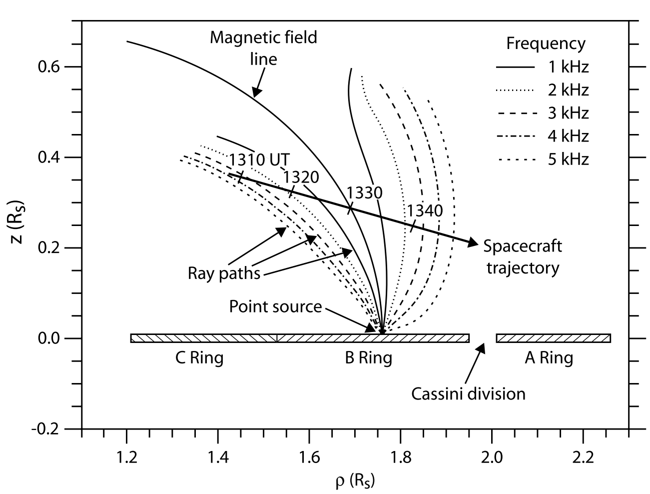

Figure 5. The best fit ray paths plotted in the (ρ, z) for a source located in the ring plane at a radial distance of 1.76 R_S.

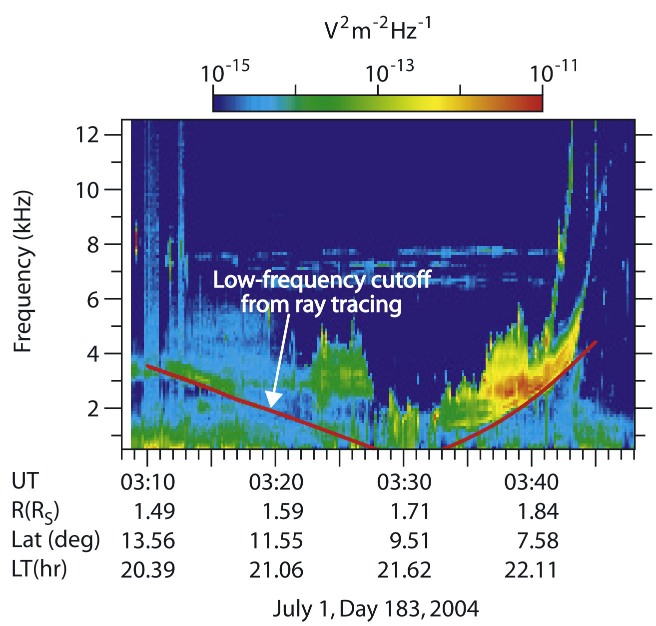

Figure 6. A comparison of the best fit low-frequency cutoff (red) computed from the ray paths shown in Figure 5 with the observed spectrum of the auroral hiss. The best fit is based on source located in the ring plane at a distance of 1.76 R_S from the center of Saturn.

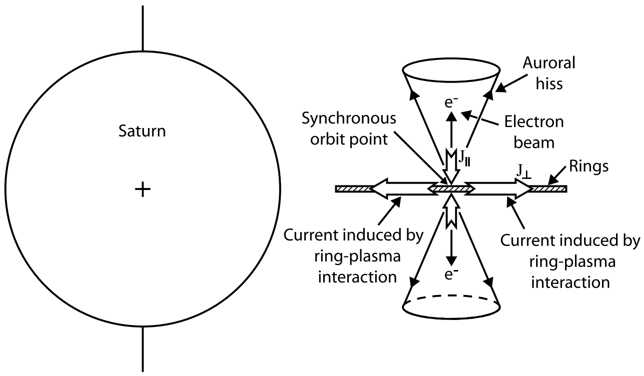

Figure 7. A sketch showing a proposed mechanism for generating auroral hiss from field-aligned electron beams near Saturn's synchronous orbit point. In this model the electron beam would be part of a current system induced in the ring plane by an interaction between the rings (including any associated gas) and the corotating magnetospheric plasma.

that there are two electron beams directed symmetrically north and south away from the rings at about 1.76 R_S as shown in Figure 7. What then is the source of these electron beams? We note that the computed source position (ρ = 1.76 R_S) is very close to Saturn's synchronous orbit point (ρ_S = 1.86 R_S), which is the point where the Keplerian velocity of the ring particles matches the corotational velocity of Saturn's magnetosphere. Since an electron beam is often the charge carrier in a field-aligned current, this observation suggests that a field-aligned current is directed into the ring near the synchronous point as shown in Figure 7. How then could such a field-aligned current be produced? The proximity to the synchronous point suggests an obvious possibility, namely that the current is produced by an interaction between the rings and the corotating magnetospheric plasma. Since the ring particles and any associated neutral gas are moving faster than the corotating magnetospheric plasma inside of the synchronous point, and slower outside of the synchronous point, it is easily demonstrated from basic principles of magnetohydrodynamics that any effective drag force between the ring particles (including gases associated with the rings) and the corotating magnetospheric plasma must be balanced by a $\mathbf{J} \times \mathbf{B}$ force caused by a perpendicular current, $J_\perp$, that is directed radially along the ring plane. Several types of ring-plasma interactions could produce this drag force. For example, if the collision frequency near the ring is sufficiently large to produce a finite transverse (Pedersen) conductivity then in the ring frame of reference the $\mathbf{E}' = -\Delta\mathbf{V} \times \mathbf{B}$ electric field caused by the differential velocity between the ring particle and the corotating magnetospheric plasma $\Delta\mathbf{V} = \mathbf{V}_{plasma} - \mathbf{V}_{ring}$ acts to drive a current inward toward Saturn inside of the synchronous point and outward away from Saturn outside of the synchronous point. In steady state the current continuity equation then demands that a north-south field-aligned current, $J_\|$, must exist that is directed symmetrically inward toward the ring plane as shown in Figure 7. In the tenuous plasma that exists in the region away from the ring plane, this field-aligned current would most likely be carried by an electron beam. The electron beam would most likely be accelerated by a parallel electric field in the vicinity of the rings, very similar to the electron acceleration that is thought to be responsible for the terrestrial aurora. This ring plasma interaction would ultimately drive a large-scale current system that links the rings to Saturn's ionosphere as shown in Figure 8. A possibly similar current system can be seen in a MHD simulation of the ring plasma interaction discussed by *Gombosi et al.* [2000].

[11] In addition to the Pedersen conductivity there are other mechanisms that could drive perpendicular currents near the rings. For example, it is easy to show that any process that leads to ionization of the gases associated with the rings automatically causes a transverse current when these particles are picked up and accelerated by the co-rotating magnetospheric plasma [*Goertz*, 1980]. Charging of dust particles associated with the rings can also induce perpendicular currents. Because of the large uncertainties in the basic parameters involved, it is difficult at the present time to determine which of these processes is most important.

[12] Although the above model has some attractive features, there are several details that are still difficult to explain. First, why is the auroral hiss source located at 1.76 R_S? Although the radial component of the perpendicular current, $J_\perp$, changes sign at the synchronous point (ρ_S = 1.86) and yields the correct direction for the field-aligned current, it is not clear why the electron beam is located at 1.76 R_S. Although the perpendicular current reverses sign at the synchronous point, unless there is a totally unexpected radial variation in the ring-plasma interaction, it is easily verified that the perpendicular current should be a smooth and continuous function of R in the vicinity of the synchronous point. Since the parallel current is proportional to the radial derivative of the perpendicular current, $J_\| \sim -dJ_\perp/dR$, then the field-aligned current should be smooth and continuous in the vicinity of the synchronous point. Therefore why is the electron beam located where it is, i.e., at 1.76 R_S? A possible hint can be seen in the electron density profile (see Figure 4). As can be seen, the electron density has a very pronounced minimum in the region where the auroral hiss is generated. Since the ability of a plasma to carry a field-aligned current depends greatly on the density of the plasma, this suggests that the parallel electric field required to accelerate the electron beam only develops in the very low density region around the density

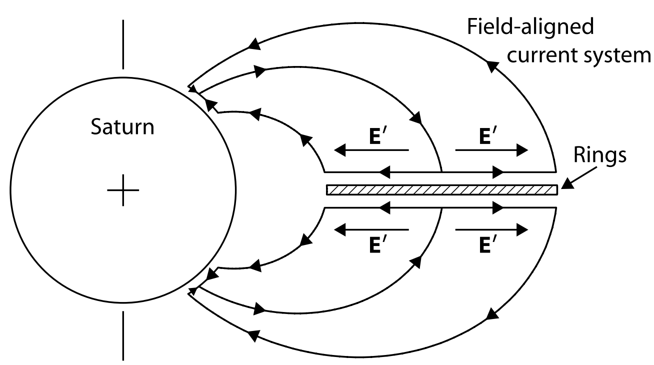

Figure 8. The proposed large-scale current system that would be induced in Saturn's magnetosphere by the interaction of the rings (including any associated gas) with the corotating magnetospheric plasma.

minimum. A similar process is believed to occur in the terrestrial aurora electron acceleration. If the location of the electron beam is determined by the density minimum then we face the questions of what causes the density minimum and why is it located at 1.76 R_S. This question has already been posed in an earlier paper by *Gurnett et al.* [2005], and at the present time we only have some tentative suggestions. The proximity to the synchronous point, where the gravitational force dominates inside of the synchronous point and the centrifugal force dominates outside, suggests that this may be the dividing point in the radial plasma flow, with the plasma diffusing inward toward Saturn inside of the synchronous point and outward away from Saturn outside. The divergence in this radial flow would naturally lead to a deep density minimum near the dividing point. Just why the density minimum is located slightly inside of the synchronous point is unknown. An inward shift would occur if the plasma over the rings is super-rotating with respect to Saturn (i.e., rotating faster than synchronous rotation). This could happen if the interaction with the faster moving ring particles inside of the synchronous point led to an overall increase in the corotational velocity, for example, due to a viscous-like radial transport of angular momentum. The required shift in the corotational velocity is quite small, only about 8 percent, probably much too small to be resolved by any of the instruments on Cassini. We also note that the scale height required to fit the low-frequency cutoff of the auroral hiss increased considerably near the density minimum, which suggests a change in the plasma temperature, with substantially higher temperatures in the region beyond the synchronous point than in the region inside. At present we have no explanation of why such a plasma temperature increase should occur, nor do we have any measurements that would either support or deny the existence of such a temperature increase. However, it does suggest that substantially different dynamical processes may be acting on the plasma inside and outside of the auroral hiss source region. Finally, we note that the density minimum is remarkably similar to the electron density depletion that occurs along the terrestrial auroral field lines, in the region where the auroral electron acceleration is thought to occur [*Calvert*, 1981; *Persoon et al.*, 1988]. At Earth this density depletion is believed to be caused by an intense flow of ions out of the ionosphere in response to transverse wave electric fields that develop in the auroral field-aligned current system. Perhaps the ionosphere-like plasma that exists near Saturn's rings is being depleted by a similar ion outflow in the region where the auroral hiss is produced.

[13] **Acknowledgments.** This research has been supported by NASA through contract number 961152 with the Jet Propulsion Laboratory.

[14] Lou-Chuang Lee thanks Mihaly Horanyi and John D. Richardson for their assistance in evaluating this paper.

References

Calvert, W. (1981), The auroral plasma cavity, *Geophys. Res. Lett.*, *8*, 919–921.

Farrell, W. M., and D. A. Gurnett (1988), An analysis of whistler mode radiation from the Spacelab 2 electron beam, *J. Geophys. Res.*, *93*, 153–161.

Gledhill, J. A. (1967), Magnetosphere of Jupiter, *Nature*, *214*, 155–156.

Goertz, C. K. (1980), Io's interaction with the plasma torus, *J. Geophys. Res.*, *85*, 2949–2956.

Gombosi, T. I., D. L. De Zeeuw, C. P. T. Groth, K. C. Hansen, K. Kabin, and K. G. Powell (2000), MHD simulations of current systems in planetary magnetospheres: Mercury and Saturn, in *Magnetospheric Current Systems*, *Geophys. Monogr. Ser.*, vol. 118, edited by S. Ohtani et al., pp. 363–370, AGU, Washington, D. C.

Gurnett, D. A. (1966), A satellite study of VLF hiss, *J. Geophys. Res.*, *71*, 5599–5615.

Gurnett, D. A., and A. Bhattacharjee (2005), *Introduction to Plasma Physics with Space and Laboratory Applications*, p. 123, Cambridge Univ. Press, New York.

Gurnett, D. A., and L. A. Frank (1972), VLF hiss and related plasma observations in the polar magnetosphere, *J. Geophys. Res.*, *77*, 172–190.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf (1979), Auroral hiss observed near the Io plasma torus, *Nature*, *280*, 767–770.

Gurnett, D. A., S. D. Shawhan, and R. R. Shaw (1983), Auroral hiss, z mode radiation, and auroral kilometric radiation in the polar magnetosphere: DE 1 observations, *J. Geophys. Res.*, *88*, 329–340.

Gurnett, D. A., W. S. Kurth, J. T. Steinberg, P. M. Banks, R. I. Bush, and W. J. Raitt (1986), Whistler-mode radiation from the Spacelab 2 electron beam, *Geophys. Res. Lett.*, *13*, 225–228.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, *114*, 395–463.

Gurnett, D. A., et al. (2005), Radio and plasma wave observations at Saturn from Cassini's approach and first orbit, *Science*, *307*, 1255–1259.

Hill, T. W., and F. C. Michel (1976), Heavy ions from the Galilean satellites and the centrifugal distortion of the Jovian magnetosphere, *J. Geophys. Res.*, *81*, 4561–4565.

Matson, D. L., L. J. Spilker, and J.-P. Lebreton (2002), The Cassini/Huygens mission to the saturnian system, *Space Sci. Rev.*, *104*, 1–58.

McIlwain, C. E. (1961), Coordinates for mapping the distribution of magnetically trapped particles, *J. Geophys. Res.*, *66*, 3681–3691.

Morgan, D. D., D. A. Gurnett, W. S. Kurth, and F. Bagenal (1994), The source of Jovian auroral hiss observed by Voyager 1, *J. Geophys. Res.*, *99*, 21,213–21,224.

Mosier, S. R., and D. A. Gurnett (1969), VLF measurements of the Poynting flux along the magnetic field with the Injun 5 satellite, *J. Geophys. Res.*, *74*, 5675–5687.

Persoon, A. M., D. A. Gurnett, W. K. Peterson, J. H. Waite Jr., J. L. Burch, and J. L. Green (1988), Electron density depletions in the nightside auroral zone, *J. Geophys. Res.*, *93*, 1871–1895.

Santolík, O., and D. A. Gurnett (2002), Propagation of auroral hiss at high altitudes, *Geophys. Res. Lett.*, *29*(10), 1481, doi:10.1029/2001GL013666.

Santolík, O., A. M. Persoon, D. A. Gurnett, P. M. E. Decreau, J. S. Pickett, O. Marsalek, M. Maksimovic, and N. Cornilleau-Wehrlin (2005), Drifting field-aligned density structures in the night-side polar cap, *Geophys. Res. Lett.*, *32*, L06106, doi:10.1029/2004GL021696.

Stix, T. H. (1992), *The Theory of Plasma Waves*, McGraw-Hill, New York.

Waite, J. H., et al. (2005), Oxygen ions observed near Saturn's A ring, *Science*, *307*, 1260–1262.

Young, D. T., et al. (2005), Composition and dynamics of plasma in Saturn's magnetosphere, *Science*, *307*, 1262–1266.

Xin, L., D. A. Gurnett, and M. G. Kivelson (2006), Whistler-mode auroral hiss emissions observed near Jupiter's moon Io, *J. Geophys. Res.*, *111*, A04212, doi:10.1029/2005JA011411.

D. A. Gurnett, G. B. Hospodarsky, W. S. Kurth, O. Santolík, and L. Xin, Department of Physics and Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, IA 52242, USA. (lei-xin@uiowa.edu)