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A north-south difference in the rotation rate of auroral hiss at Saturn: Comparison to Saturn's kilometric radio emission

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[1] Broadband whistler-mode emissions, commonly observed by the Cassini spacecraft at high latitudes in Saturn's magnetosphere at frequencies below about 100 Hz, have characteristics very similar to auroral hiss observed at high latitudes in Earth's magnetosphere. In contrast to terrestrial auroral hiss, which shows no obvious rotational modulation, Saturnian auroral hiss shows a very pronounced rotational modulation. We show that the rotation period of the auroral hiss is different in the northern and southern hemispheres, with a period of about 10.6 hours in the northern hemisphere and about 10.8 hours in the southern hemisphere. To within experimental error the rotation periods in the two hemispheres match the rotation periods of Saturn Kilometric Radiation, an intense radio emission generated along the auroral field lines at frequencies from about 20 to 500 kHz. These north–south asymmetries have potentially important implications on how angular momentum is transferred from the planet to the magnetospheric plasma. **Citation:** Gurnett, D. A., A. M. Persoon, J. B. Groene, A. J. Kopf, G. B. Hospodarsky, and W. S. Kurth (2009), A north-south difference in the rotation rate of auroral hiss at Saturn: Comparison to Saturn's kilometric radio emission, *Geophys. Res. Lett.*, *36*, L21108, doi:10.1029/2009GL040774.

1. Introduction

[2] Recently *Gurnett et al.* [2009] reported the discovery of a north–south difference in the rotational modulation rate of Saturn Kilometric Radiation (SKR), which is an intense radio emission generated at frequencies from about 20 to 500 kHz along Saturn's auroral magnetic field lines [*Kaiser et al.*, 1980; *Desch and Kaiser*, 1981; *Zarka*, 1998; *Galopeau and Lecacheux*, 2000; *Lamy et al.*, 2008]. In this paper we report a nearly identical north–south difference in the rotational rate of auroral hiss at Saturn. These observations provide strong confirmation of a fundamental north–south asymmetry in the rotation rate of auroral phenomena at Saturn, an asymmetry that likely has important implications on how the planetary rotation is coupled to the magnetospheric plasma.

2. Auroral Hiss at Earth

[3] Auroral hiss is a broadband whistler-mode emission that is commonly observed in association with aurora at frequencies below the electron cyclotron frequency and plasma frequency. First discovered from early ground-based very-low-frequency radio observations [*Martin et al.*, 1960], this radio emission has since been extensively studied using very-low-frequency (VLF) radio receivers on both low and high altitude polar-orbiting spacecraft [*Gurnett and O'Brien*, 1964; *Gurnett et al.*, 1983; *Ergun et al.*, 2003]. Auroral hiss often has a characteristic V-shaped appearance on a frequency-time spectrogram, and has been variously called V-shaped hiss [*Gurnett*, 1966], saucers [*James*, 1976], or funnel-shaped emissions [*Gurnett et al.*, 1983]. The V-shaped spectrum is a propagation effect that arises because the wave normal is near the whistler-mode resonance cone, which causes the wave energy to propagate at an angle to the magnetic field line that increases as the frequency increases. Poynting flux measurements of the direction of energy propagation show that two types of auroral hiss are observed, one propagating upward along the magnetic field line, and the other propagating downward [*Mosier and Gurnett*, 1969]. Comparisons with charged particle measurements clearly show that both types of auroral hiss are produced by magnetic field-aligned electron beams with energies ranging from a few hundred eV to several keV. The downward propagating auroral hiss is produced by downward moving electron beams [*Gurnett*, 1966], and the upward propagating auroral hiss is produced by upward moving electron beams [*Lin et al.*, 1984; *Ergun et al.*, 2003]. These upward and downward-directed electron beams are believed to be part of the large-scale magnetospheric current system that is responsible for the aurora [*Gurnett and Frank*, 1972]. Auroral hiss is also usually accompanied at lower frequencies by broadband electrostatic noise [*Gurnett and Frank*, 1977], now thought to be transient solitary structures produced by the same electron beam responsible for the auroral hiss [*Ergun et al.*, 2003].

[4] Although once thought to be produced by incoherent Cerenkov radiation [*Jorgensen*, 1968], auroral hiss is now believed to be generated by a coherent beam-plasma interaction [*Maggs*, 1976] at the Landau resonance velocity, $\omega/k_{\parallel} = v_{\parallel}$. Very similar broadband whistler-mode emissions, excited at the Landau resonance velocity, have been produced by an artificial electron beam experiment on the Space Shuttle [*Farrell et al.*, 1989].

3. Auroral Hiss at Saturn

[5] Auroral hiss is commonly observed at high latitudes in Saturn's magnetosphere by the Cassini Radio and Plasma Wave Science (RPWS) instrument. For a description of this instrument see *Gurnett et al.* [2004]. A frequency-time spectrogram showing the electric field intensities of auroral

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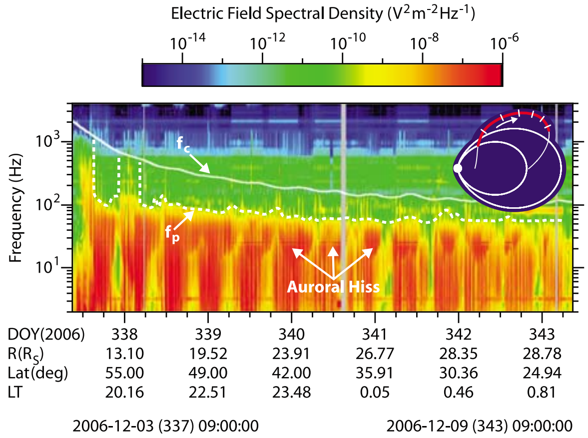

Figure 1. A frequency-time spectrogram of auroral hiss observed during a high latitude pass through the late evening side of Saturn's magnetosphere. The white line labeled f_c is the electron cyclotron frequency computed from the magnetic field as measured by the onboard magnetometer. The upper cutoff of the auroral hiss, indicated by the dashed white line, is believed to be at or near the electron plasma frequency, $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}.

hiss on the outbound leg of one such high latitude pass is shown in Figure 1. The strong emissions at frequencies below about 100 Hz are identified as auroral hiss and broadband electrostatic noise, very similar to auroral hiss observed at high latitudes in Earth's magnetosphere [*Gurnett et al.*, 1983]. The main features identifying the higher frequency emissions as auroral hiss are (1) a funnel-shaped frequency-time structure that flares outward at high frequencies; (2) a sharp upper frequency cutoff at a frequency near the electron plasma frequency, $f_p = 8980\sqrt{n_e}$ Hz, where n_e is the electron density in cm^{-3}; and (3) the presence of a weak magnetic component (not shown) that is consistent with propagation in the whistler mode. Computations of the Poynting flux, $\mathbf{E} \times \mathbf{H}$, from onboard measurements of the electric and magnetic field waveforms, show that the waves are propagating upward from a source below the spacecraft. Ray tracing calculations of auroral hiss propagating upward from a low-altitude point source similar to those performed by *Gurnett et al.* [1983] show that the radiation flares out in a funnel-shaped beam that is aligned along the magnetic field line, as illustrated in Figure 2.

[6] One important difference compared to terrestrial auroral hiss is that Saturnian auroral hiss displays a well-defined modulation at approximately the 10.6 to 10.8 hour rotation period of the planet (see Figure 1). After correcting for the tilt of Earth's magnetic axis relative to its rotational axis, terrestrial auroral hiss does not display a comparable rotational modulation. That Saturnian auroral hiss has any rotational modulation at all is a puzzle, since Saturn's magnetic axis is known to be aligned almost exactly along its rotational axis (<1°). However, this puzzle is not unique to auroral hiss, since it has been known from early Voyager observations [*Desch and Kaiser*, 1981] that SKR has a clock-like modulation at a period that is close to the planetary rotation period. Even more puzzling, it is now known that the SKR modulation consists of two distinct components [*Kurth et al.*, 2008], one originating from the northern auroral region with a period of about 10.6 h, and the other originating from the southern auroral region with a period of about 10.8 h [*Gurnett et al.*, 2009]. The purpose of this paper is to determine if the rotation period of auroral hiss has a similar north–south asymmetry.

[7] In order to determine the modulation period of the auroral hiss to an accuracy comparable to the accuracy with which the SKR period can be measured, i.e., better than 1%, the period must be averaged over very long intervals, at least 100 days or more. Since the orbital period of Cassini is typically about 10 to 30 days, this requires averaging over many orbits. At present there are only two intervals where the spacecraft reached sufficiently high latitudes, $|\mathrm{Lat}| > 30°$, for an adequately long time, >100 days, to provide a useful determination of the modulation period. 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. Since data gaps are introduced as the spacecraft passes through low latitudes twice per orbit, the measurements are aliased by the spacecraft orbital motion. However, this aliasing is generally not a problem since the modulation periods of interest (approximately 10.6 to 10.8 hours) are well separated from the spacecraft orbital period. Since it is difficult to design an algorithm to automatically identify auroral hiss, the procedure we used was to visually identify a beginning and an ending time for the auroral hiss during each rotation of the planet. The auroral hiss was assigned a normalized intensity of one when the hiss is present, and zero when the hiss is absent. If no rotational modulation could be identified, for example when the spacecraft was passing through the equator, the intensities were flagged "no data" and these times were ignored in the subsequent processing.

[8] To compute the rotational modulation spectrum, the normalized auroral hiss intensities were sorted and averaged in 1 degree bins in longitude, λ, for a series of assumed rotation rates, ω. Northern and southern hemisphere data were processed separately. For each ω the resulting averages were fit to a sinusoidal function of longitude, $A\sin[2\pi(\lambda - \varphi)/360°]$, thereby giving the amplitude, A, and phase, φ, of whatever modulation might be present. The normalized modulation power, P, at this specific rotation rate was taken to be proportional to the square of the peak-to-peak amplitude of the sine wave fit, i.e., $P = (2A)^2$. This is essentially the same procedure used by *Gurnett et al.* [2009] to analyze the rotational modulation of SKR. Since it was not clear whether the rotational modulation would be best represented by a clock-like source (such as the SKR) or a rotating beam source, two longitudes were used. For a clock-like source the longitude of the Sun, $\lambda_{Sun} = \omega T$, was used, where T is the Universal Time (UT) at the spacecraft, and for a rotating beam source the longitude of the spacecraft, $\lambda_{SC} = \omega T + (12 - LT_{SC}) \times 15°$, was used, where LT_{SC} is the local time of the spacecraft.

[9] The rotational modulation spectrum of auroral hiss detected in the northern hemisphere during the first series of high latitude orbits is shown in Figure 2. Two plots are shown, one with a black line for a rotating beam source, and the other with a red line for a clock-like source. As can be

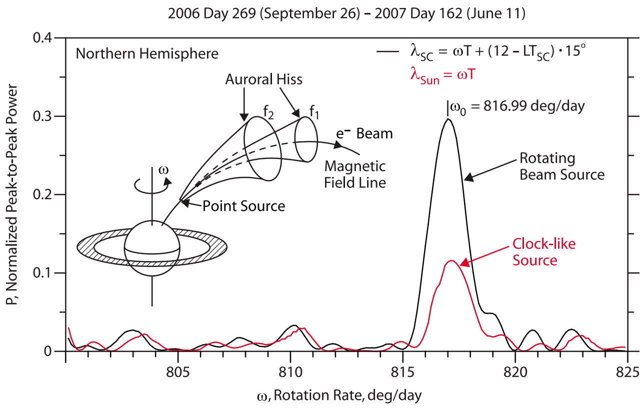

Figure 2. The diagram on the left shows expected ray paths for auroral hiss propagating upward along the magnetic field from a point source located close to Saturn. For propagation near the resonance cone the ray paths form a funnel around the magnetic field line, the angle of which increases as the frequency increases, $f_2 > f_1$. The plot on the right shows the modulation power of auroral hiss observed in the northern hemisphere as a function of an assumed rotation rate, ω. Two longitudes were used in this analysis, (1) the longitude of the spacecraft, λ_{SC}, which is appropriate for a rotating beam source (black line), and (2) the longitude of the Sun, λ_{Sun}, which is appropriate for a clock-like source (red line). The results strongly favor a rotating beam source.

seen the spectrum for the rotating beam source has a very sharp well-defined peak, with a peak amplitude that is almost three times that for the clock-like source. This large difference indicates that the source is almost certainly a rotating beam. The rotation rate obtained from a parabolic fit near the peak of the spectrum gives a rotation rate of 817.0 ± 0.9 deg/day, where the plus and minus uncertainty limits are at one-half the amplitude of the spectral peak.

4. Comparison to Saturn Kilometric Radiation

[10] A comparison of the rotational modulation rate of the auroral hiss and the SKR is given in Figure 3. Figure 3a shows the latitude of the spacecraft, and Figures 3b and 3c show frequency-time spectrograms of the rotational modulation rates of SKR in the northern and southern hemispheres similar to those given by *Gurnett et al.* [2009]. The rotation period of the auroral hiss in the northern hemisphere for the first interval (from Figure 2) is shown by the white dot at the center of this interval, which is day 33, 2007. The white horizontal bar through the white dot gives the duration of the analysis interval. The vertical size of the dot is comparable to the uncertainty in the rotation rate. As can be seen the rotation rate of the auroral hiss is almost exactly the same as the rotational modulation rate of the SKR. Unfortunately, because the spacecraft was making only very brief (less than one day) excursions to high southerly latitudes, it was not possible to obtain a reliable measurement of the rotation period of the auroral hiss in the southern hemisphere during this time interval.

[11] A much better opportunity to obtain simultaneous measurements of the rotation rate of the auroral hiss in both hemispheres occurred during the second interval of high latitude observations. During this interval the spacecraft orbit was such that good auroral hiss observations, with very well-defined rotational modulations in both the northern and southern hemispheres, could be obtained from about day 358, 2008, to day 167, 2009. Using the same spectrum analysis procedure as in Figure 2 the rotation rates of the auroral hiss in the northern and southern hemispheres during this interval were found to be 813.9 ± 0.8 deg/day and 800.7 ± 0.9 deg/day, respectively. These rotation rates are shown in Figure 3 by the white dots at the center of the interval, which is day 79, 2009. The horizontal white lines again indicate the duration of the analysis intervals and the vertical size of the dots are comparable to the uncertainties in the rotation rates. As can be seen, the auroral hiss rotation rates in the northern and southern hemispheres match almost exactly the SKR rotational modulation rates in those hemispheres. The SKR rotation rates in the northern and southern hemispheres averaged over this same time interval were 813.8 ± 0.9 deg/day and 801.0 ± 1.1 deg/day, respectively.

5. Discussion

[12] We have shown that the rotational modulation periods of auroral hiss and SKR in a given hemisphere are nearly identical, i.e., about 10.6 hours in the northern hemisphere and 10.8 hours in the southern hemisphere. These observations provide a striking confirmation of the north–south asymmetry of the rotational modulation of SKR first reported by *Gurnett et al.* [2009]. It is interesting to note that even though they occur at almost the same rate, the rotational modulation processes involved in the auroral hiss and the SKR are fundamentally different. The SKR modulation is known to be clock-like, with the radiation

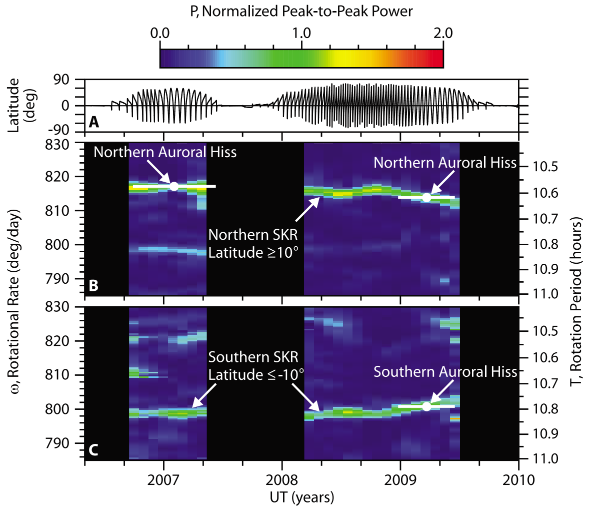

Figure 3. (a) Longitude of the spacecraft and adapted from *Gurnett et al.* [2009], the color-coded modulation power for SKR observed (b) in the northern hemisphere and (c) in the southern hemisphere. The white dots and associated horizontal bars show the corresponding rotation rates of auroral hiss observed in the two hemispheres. The rotation rates of the auroral hiss are seen to be in almost exact agreement with the SKR rotational modulation rates.

blinking on and off from a high-latitude source in the late local morning [*Desch and Kaiser*, 1981], whereas we have shown that the auroral hiss modulation is caused by a rotating beam, like the rotating beacon at an airport. Also, the radio emission mechanisms are quite different. SKR is believed to be generated via the cyclotron maser mechanism [*Wu and Lee*, 1979] by an anisotropic distribution of electrons accelerated downward along the magnetic field lines by parallel electric fields, whereas auroral hiss detected by Cassini is believed to be generated by an electron beam moving upward along the magnetic field lines. Since the SKR is known to be most strongly generated in the late local morning side of the magnetosphere, it has been postulated that the radiation switches on as some rotating plasma feature is carried through this region [*Gurnett et al.*, 2007], perhaps due to enhanced reconnection [*Burch et al.*, 2008] or some other physical process that arises as the plasma interacts with the morning-side magnetopause. With this general picture in mind, it is interesting to investigate the phase difference between the auroral hiss and the SKR modulations. For the second time interval analyzed, where we have the best data, the average phase difference can be determined from the phases of the best sine function fit to the auroral hiss and SKR rotational modulations. The longitude differences between the peak auroral hiss and the SKR intensities, $\varphi_{SC}(\mathrm{Hiss}) - \varphi_{Sun}(\mathrm{SKR})$, at the time of maximum SKR intensity are found to be $-50°$ in the northern hemisphere, and $-112°$ in the southern hemisphere. From the previously given definitions of λ_{SC} and λ_{Sun} it is easy to show that the local time, $\mathrm{LT}_{\mathrm{Hiss}}$, of the peak auroral hiss intensity at the time of maximum SKR intensity is given by the equation $\varphi_{SC}(\mathrm{Hiss}) - \varphi_{Sun}(\mathrm{SKR}) = (12 - \mathrm{LT}_{\mathrm{Hiss}}) \times 15°$. Using the measured phase differences, $-50 \pm 10°$ and $-112 \pm 17°$, this equation yields $\mathrm{LT}_{\mathrm{Hiss}} = 15.3 \pm 0.7$ hours in the northern hemisphere and $\mathrm{LT}_{\mathrm{Hiss}} = 19.5 \pm 1.1$ hours in the southern hemisphere. These phase relations clearly show that the auroral hiss source is rotating through the local afternoon side of the magnetosphere at the time that the SKR reaches maximum intensity in the late local morning side of the magnetosphere. Since the auroral hiss is believed to be generated by up-going electrons accelerated by parallel electric fields and the SKR is generated by comparably accelerated down-going electrons, these results suggest that the currents carried by these electrons may be part of a large-scale rotating current system of the type proposed by *Southwood and Kivelson* [2007]. In this system the current flows down the high-latitude magnetic field lines on one side of the magnetosphere, horizontally through the ionosphere, and then upward along the high-latitude magnetic field lines on the other side of the magnetosphere. If such a current system is involved in the generation of the auroral hiss and SKR, then the currents would have to consist of two components that rotate at different rates in the two hemispheres, which at the present time is quite difficult to comprehend. Clearly, considerable further study is needed to understand how auroral hiss and SKR are related to Saturn's rotating magnetic fields and plasmas.

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References

Burch, J. L., J. Goldstein, P. Mokashi, W. S. Lewis, C. Paty, D. T. Young, A. J. Coates, M. K. Dougherty, and N. Andre (2008), On the cause of Saturn's plasma periodicity, *Geophys. Res. Lett.*, *35*, L14105, doi:10.1029/2008GL034951.

Desch, M. D., and M. L. Kaiser (1981), Voyager measurements of the rotation period of Saturn's magnetic field, *Geophys. Res. Lett.*, *8*, 253–256, doi:10.1029/GL008i003p00253.

Ergun, R. E., C. W. Carlson, J. P. McFadden, R. J. Strangeway, M. V. Goldman, and D. L. Newman (2003), Fast auroral snapshot satellite observations of very low frequency saucers, *Phys. Plasmas*, *10*, 454–462, doi:10.1063/1.1530160.

Farrell, W. M., D. A. Gurnett, and C. K. Goertz (1989), Coherent Cerenkov radiation from the Spacelab 2 electron beam, *J. Geophys. Res.*, *94*, 443–452, doi:10.1029/JA094iA01p00443.

Galopeau, P., and A. Lecacheux (2000), Variations of Saturn's radio rotation period measured at kilometric wavelengths, *J. Geophys. Res.*, *105*, 13,089–13,102, doi:10.1029/1999JA005089.

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

Gurnett, D. A., and L. A. Frank (1972), VLF hiss and related plasma observations in the polar magnetosphere, *J. Geophys. Res.*, *77*, 172–190, doi:10.1029/JA077i001p00172.

Gurnett, D. A., and L. A. Frank (1977), A region of intense plasma wave turbulence on auroral field lines, *J. Geophys. Res.*, *82*, 1031–1050, doi:10.1029/JA082i007p01031.

Gurnett, D. A., and B. J. O'Brien (1964), High-latitude geophysical studies with satellite Injun 3: 5. Very-low-frequency electromagnetic radiation, *J. Geophys. Res.*, *69*, 65–89, doi:10.1029/JZ069i001p00065.

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, doi:10.1029/JA088iA01p00329.

Gurnett, D. A., et al. (2004), The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, *114*, 395–463, doi:10.1007/s11214-004-1434-0.

Gurnett, D. A., et al. (2007), The variable rotation period of the inner region of Saturn's plasma disk, *Science*, *316*, 442–445, doi:10.1126/science.1138562.

Gurnett, D. A., A. Lecacheux, W. S. Kurth, A. M. Persoon, J. B. Groene, L. Lamy, P. Zarka, and J. F. Carbary (2009), Discovery of a north–south asymmetry in Saturn's radio rotation period, *Geophys. Res. Lett.*, *36*, L16102, doi:10.1029/2009GL039621.

James, H. G. (1976), VLF saucers, *J. Geophys. Res.*, *81*, 501–514, doi:10.1029/JA081i004p00501.

Jorgensen, T. S. (1968), Interpretation of auroral hiss measured on OGO 2 and at Byrd Station in terms of incoherent Cerenkov radiation, *J. Geophys. Res.*, *73*, 1055–1069, doi:10.1029/JA073i003p01055.

Kaiser, M. L., M. D. Desch, J. W. Warwick, and J. B. Pearce (1980), Voyager detection of nonthermal radio emission from Saturn, *Science*, *209*, 1238–1240, doi:10.1126/science.209.4462.1238.

Kurth, W. S., T. F. Averkamp, D. A. Gurnett, J. B. Groene, and A. Lecacheux (2008), An update to a Saturnian longitude system based on kilometric radio emissions, *J. Geophys. Res.*, *113*, A05222, doi:10.1029/2007JA012861.

Lamy, L., et al. (2008), Saturn kilometric radiation: Average and statistical properties, *J. Geophys. Res.*, *113*, A07201, doi:10.1029/2007JA012900.

Lin, C. S., J. L. Burch, S. D. Shawhan, and D. A. Gurnett (1984), Correlation of auroral hiss and upward electron beams near the polar cusp, *J. Geophys. Res.*, *89*, 925–935, doi:10.1029/JA089iA02p00925.

Maggs, J. E. (1976), Coherent generation of VLF hiss, *J. Geophys. Res.*, *81*, 1707–1724, doi:10.1029/JA081i010p01707.

Martin, L. H., R. A. Helliwell, and K. E. Marks (1960), Association between aurorae and very-low-frequency hiss observed at Byrd Station, Antarctic, *Nature*, *187*, 751–753, doi:10.1038/187751a0.

Mosier, S. R., and D. A. Gurnett (1969), VLF measurements of the Poynting flux along the geomagnetic field with the Injun 5 satellite, *J. Geophys. Res.*, *74*, 5675–5687, doi:10.1029/JA074i024p05675.

Southwood, D. J., and M. G. Kivelson (2007), Saturnian magnetospheric dynamics: Elucidation of a camshaft model, *J. Geophys. Res.*, *112*, A12222, doi:10.1029/2007JA012254.

Wu, C. S., and L. C. Lee (1979), A theory of the terrestrial kilometric radiation, *Astrophys. J.*, *230*, 621–626, doi:10.1086/157120.

Zarka, P. (1998), Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, *103*, 20,159–20,194, doi:10.1029/98JE01323.

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