A nightside source of Saturn's kilometric radiation: Evidence for an inner magnetosphere energy driver

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[1] During Cassini's orbit insertion about Saturn, the spacecraft passed within 1.4 R_s of the planet passing from dayside into the nightside region. During this nightside passage, the onboard Radio and Plasma Wave (RPWS) instrument surprisingly detected Saturn kilometric radiation (SKR). Prior to this encounter, it was believed that SKR originated from a high-latitude dayside source, and radio beams from such a source would not be viewable in this nearplanet night-side location. Subsequent analysis presented here reveals that this SKR did indeed originate from the near-midnight region on field lines near L ~ 10–15. Such a radio source suggests the presence of an active region in the night-side inner magnetosphere; this source possibly being near the outer edge of the icy-moon created plasma torus surrounding the planet. The implication is that some of the SKR is driven by an internal energy source that may also account for recent UV aurora observations. **Citation:** Farrell, W. M., M. D. Desch, M. L. Kaiser, A. Lecacheux, W. S. Kurth, D. A. Gurnett, B. Cecconi, and P. Zarka (2005), A nightside source of Saturn's kilometric radiation: Evidence for an inner magnetosphere energy driver, *Geophys. Res. Lett.*, *32*, L18107, doi:10.1029/2005GL023449.

1. Introduction

[2] During the two Voyager/Saturn encounters in the early 1980s, an intense nonthermal radio emission called Saturnian kilometric radiation was discovered by Voyager's Planetary Radio Astronomy experiment [*Kaiser et al.*, 1980] and Plasma Wave System [*Gurnett et al.*, 1981]. The emission was found to originate from the planet's north and south magnetic poles, extending from 3 to 1200 kHz with a source power near 10^9 W [*Kurth et al.*, 2005]. Based on overall emission occurrence and an occultation event observed by Voyager 1, the emission source location was determined to be fixed in local time near noon (as opposed to a co-rotating "search-light" source), this source positioned at relatively high magnetic latitudes [*Kaiser and Desch*, 1982; *Lecacheux and Genova*, 1983; *Galopeau*, 1992]. The location of the active magnetic field lines was consistent with that of the Saturnian polar cusp (see review by *Kaiser et al.* [1984]), further suggesting an energy source external to the planet (i.e., solar wind driven).

[3] This view of a local-time fixed source location of the SKR persisted for nearly 25 years, until *Kurth et al.* [2005] recently presented simultaneous Hubble Space Telescope UV and Cassini Radio and Plasma Wave (RPWS) instrument observations that suggest a more complicated situation. Specifically, Hubble images [*Clarke et al.*, 2005] revealed a set of longitudinally-elongated active auroral regions or "hot spots" that were not fixed in local time, but instead rotated about the pole at about 1/2 the corotation rate. As these active regions rotated in view of Cassini, the SKR proceeded to "turn on" [*Kurth et al.*, 2005]. At the time, Cassini was inbound to the planet, located at ~7.5 hr local time and 1250 Rs from the planet center.

[4] *Huff et al.* [1988] demonstrated that terrestrial AKR originates from geomagnetic field lines directly connected to discrete auroral arcs. The unique Hubble UV/Cassini radio observations [*Clarke et al.*, 2005; *Kurth et al.*, 2005] suggest a similar UV hot spot/kilometric radio source connection. As with the terrestrial case, the energetic electrons that cause the fluorescence of the upper atmospheric gases (UV aurora) also generate coherent electron cyclotron radio emission at higher altitudes [*Wu and Lee*, 1979] along the inter-connecting magnetic field lines.

[5] Unfortunately, the geometry of Cassini relative to Saturn during the Hubble UV campaign did not unambiguously rule out the Voyager-like fixed-in-local time perspective. Specifically, during the Hubble UV campaign, Cassini was located at ~7.5 hours local time, and the radio horizon (where a radio source becomes viewable) was colocated near the noon-midnight meridian. Thus, it could not be determined whether the observed "turn on" of SKR observed by Cassini was related to a spatial effect as the UV hot spot (radio source) passed over the radio horizon and into view of Cassini or, conversely, a temporal effect as the UV hot spot (radio source) passed through the active noon meridian thereby activating the radio portion of the spectrum. In the former case, the radio beam is emanating from the auroral hot spot but becomes viewable when spatial conditions are correct (Cassini above the hot spot's local radio horizon). In the latter case, the UV hot spot does not radiate cyclotron emission until it is in proximity of local noon, when the radio beam activates.

[6] To break this spatial/temporal ambiguity in the nature of SKR, observations made well away from high latitude/local noon are required. Fortunately, during the 1 July 2004 closest approach pass to Saturn, Cassini passed from dayside into nightside close to the planet, allowing a period of

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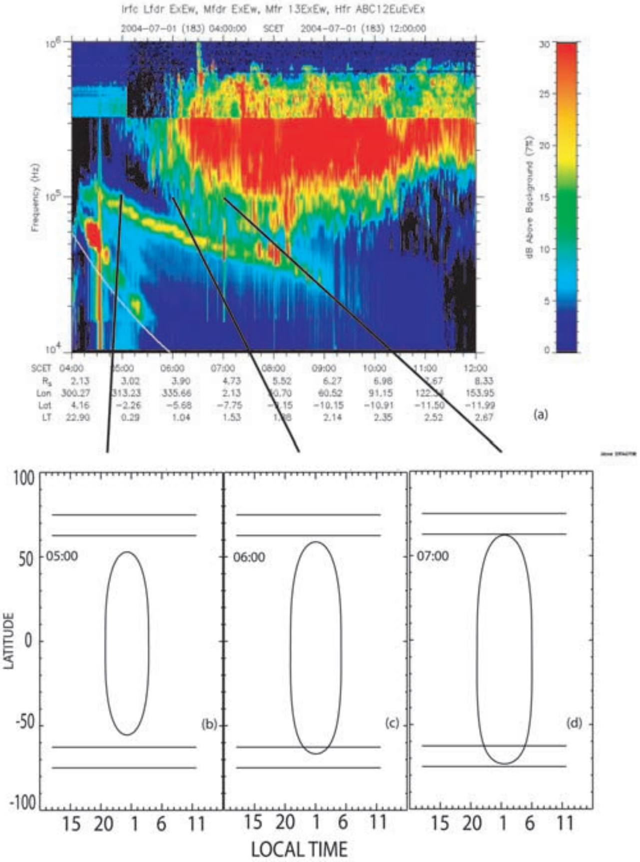

Figure 1. The radio horizon for emission at 100 kHz. (b)–(d) show a latitude/local time projection of the shell's surface. The region inside the oval represents those locations where the spacecraft is viewable (above the local radio horizon). The region between the straight lines represents the auroral region which is viewable at Cassini near 06:00 SCET.

observation when the high latitude noontime region (the Voyager source) is not in radio view.

2. Observations

[7] Figure 1a shows a frequency versus time spectrogram from 1 July 2004 when Cassini was outbound but still very close to the planet following its orbit insertion burn (SOI). From 04:00 to 12:00 SCET, the radial distance of Cassini ranged from 2.1 Rs to 8.3 Rs, with a nightside local time varying from 23 hours to near 3 hours. In the spectrogram, the downdrifting reference (white) line is the local electron cyclotron frequency derived from the Saturn Z3 magnetic field model [*Connerney et al.*, 1984]. The narrowband downdrifting emission at frequencies slight greater than this reference line is the 3/2 fc harmonic emission which drops below 10 kHz near 06:00 SCET. The second relatively intense downdrifting tone is the upper hybrid resonance, downdrifting from near 100 kHz near 04:15 SCET to 30 kHz near 09:00 SCET and fading thereafter. The most intense emission in the spectrogram is SKR, this extending quasi-continuously from 04:40 to 12:00 SCET from near 60 kHz to 700 kHz. From the Voyager perspective, the presence of this emission is somewhat surprising, since a noon source would not be visible at Cassini during the period before ~10:00 SCET.

[8] As evidence for this noon region occultation, we present a calculation of the region viewable by Cassini on the 100 kHz shell of constant electron cyclotron frequency about the planet in Figures 1b–1d. For a cyclotron maser radio source [*Wu and Lee*, 1979], emissions will originate at locations where the wave frequency at 100 kHz is near the local electron cyclotron frequency. By examining the locus of points about the planet where $f \sim f_c$ (i.e., forming a shell of constant electron cyclotron frequency) and deriving the angle between the local shell normal and Cassini, we can determine the locations that are in view of Cassini at any given time. In essence, at each location on the shell, we determine whether Cassini lies above (in-view) or below (out-of-view) the plane perpendicular to the local shell normal. This plane defines the limiting R-X mode ray path, since ray paths at angles below the plane propagate into regions of decreasing index of refraction and are thus refracted away from the surface to angles above the horizon (see the detailed ray tracing analysis at a local R-X emission source of *Calvert* [1981, Figure 2]). *Huff et al.* [1988, Figure 1] illustrates the spacecraft and radio horizon geometry from a side-viewing vantage point. Plotted in our Figure 1 is the latitude and local time of the 100 kHz shell, along with the projection of the auroral zone (between 72° and 80° latitude [see *Clarke et al.*, 2005, Figure 1]) onto the shell, this zone lying between the straight lines in the figure. The oval in the figure represents the limit of viewable regions on the shell from Cassini's perspective. The oval represents the radio horizon with the region inside the circle being viewable and the region exterior to the circle out of view (occulted by the shell itself).

[9] At 05:00 SCET (Figure 1b), Cassini was located at 3 Rs and is positioned only about 1.2 Rs from the 100 kHz shell of constant cyclotron frequency. Consequently, Cassini's field of view on the shell was limited to ~100°. The rest of the shell was not viewable from Cassini's location (i.e., Cassini is below the local horizon for these outside regions). As evident in Figure 1b, at 05:00 SCET, the radio horizon analysis indicates that Cassini could not view the locations that map to the auroral zone where SKR originates. Looking at Figure 1a near 05:00 SCET and near a frequency of 100 kHz, we see that SKR was not observed by Cassini at this time, consistent with the obscuration of the source predicted by the radio horizon analysis. However, near 06:00 SCET (Figure 1c), Cassini had receded far enough from the shell to allow a larger field of view now encompassing the area connected to the southern auroral zone between hours 23 and 3 local time. Note in Figure 1a that SKR was indeed observed to turn on near this time. However, this auroral SKR originated not from a noontime source, but from a near-midnight source. No post-dawn to pre-dusk location is viewable in this geometry. By 07:00 SCET, emission was very strong and steady, with a large section of the nightside southern auroral oval in view (Figure 1d).

[10] Figures 2a–2d is a similar analysis but now for 300 kHz. Note that the emission again was consistent with locations viewable only on the nightside hemisphere. At 05:00 SCET, the emission commenced as the nightside southern auroral region came into Cassini's view (Figure 2c).

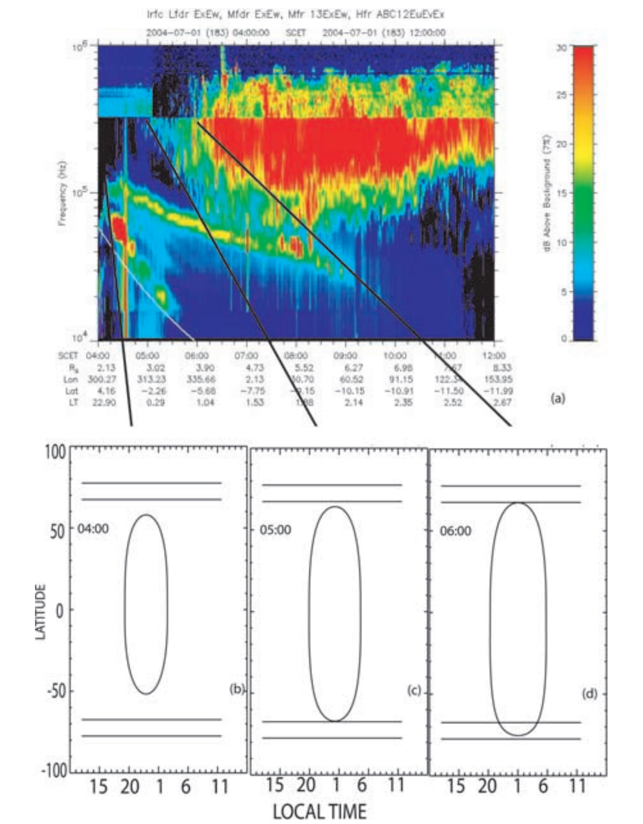

Figure 2. The radio horizon for emission at 300 kHz. (b)–(d) show a latitude/local time projection of the shell's surface. The region inside the oval represents those locations where the spacecraft is viewable (above the local radio horizon). The region between the straight lines represents the auroral region, which is viewable at Cassini after 05:00 SCET.

By 06:00 SCET, the emission was strong and correspondingly a large section of the nightside southern auroral region was in Cassini's view.

[11] Figure 3 shows the polarization with white indicative of apparent left-handed emission and black indicative of apparent right-handed emission. Note that between hours 05:00–06:00 SCET the emission was primarily left-handed, and is consistent with observing an R-X emission source from the southern nightside region with inward-directed magnetic field geometry. Near 06:00 SCET, the apparent polarization reversed, this due to the passage of the southern SKR source region through the Cassini antenna electrical plane in association with a series of spacecraft roll-like maneuvers. In general, an apparent polarization reversal will occur as a polarized source changes relative position from above to below the antenna electrical plane since the wave's intrinsic circular polarization is sensed a quarter-cycle out of phase by the antenna elements. After 08:00 SCET, the sub-spacecraft local time slowly shifts the source from below to above the electrical plane, thereby returning the polarization to apparent left handed (consistent with a southern RX polarized source).

[12] Cassini also has direction finding (DF) capability [*Gurnett et al.*, 2004; *Vogl et al.*, 2004] and preliminary results indicate the presence of a southern SKR source with k-vectors directed (mostly) outward from locations near the noon-midnight central meridian [A. Lecacheux, personal communication]. The radio horizon analysis presented here indicates that only the midnight portion of this meridian is viewable to Cassini; a noon source is effectively blocked by the shell of constant cyclotron frequency, at altitudes below which rays cannot propagate.

3. Discussion

[13] Figures 1 and 2 reveal two observations associated with the SKR source: First, the locations viewable between 05:00-06:00 SCET, consistent with the emission commencement, were near local midnight. Second, as indicated in Figure 1c and 2c, when emission does commence, the radio horizon has extended into the auroral zone, but only to the relatively low latitudes between 72° and 75°. In essence, the emission turn-on (the frequency downdrifting edge of the emission) is consistent with the radio horizon at a given frequency intercepting the low latitude portion of the auroral zone. Such a nightside-extending low latitude location corresponds to L-shells of 10 to 15. These conclusions suggest an auroral energy source interior/within the magnetosphere that is active in the nightside hemisphere.

[14] One possible source of such activity is the outer edge of the ion torus formed by sputtering and subsequent ionization of neutrals from the inner icy moons and E-ring of Saturn [*Richardson and Jurac*, 2004]. As indicated in their Figure 1, an electron torus is present about Saturn, with peak densities ~100 el/cc near 3 Rs. Torus densities progressively decrease with increasing radial distance, with values near 1 el/cc near 12 Rs. The Cassini RPWS experiment consistently detects this torus with each planetary swingby, with densities observed near 100 el/cc near 2.5 Rs as derived by upper hybrid emissions and the Langmuir probe [*Gurnett et al.*, 2005].

[15] Recently, *Clarke et al.* [2005] obtained a "big picture" view of Saturn's southern aurora using Hubble Space Telescope UV capability. As stated, the morphology of Saturn's aurora is very complicated, being a simple low-latitude partial ring structure during quiescent periods to intensifications extending up the poles during active periods.

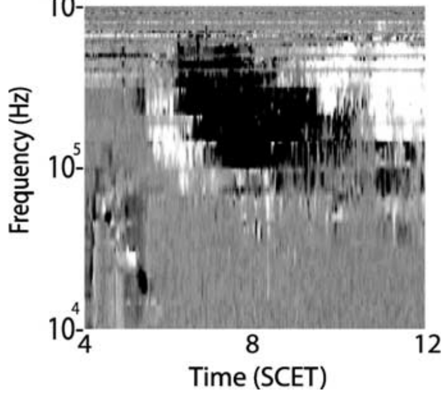

Figure 3. Emission polarization, with white being apparent left-handed and black being apparent right-handed in the spacecraft frame.

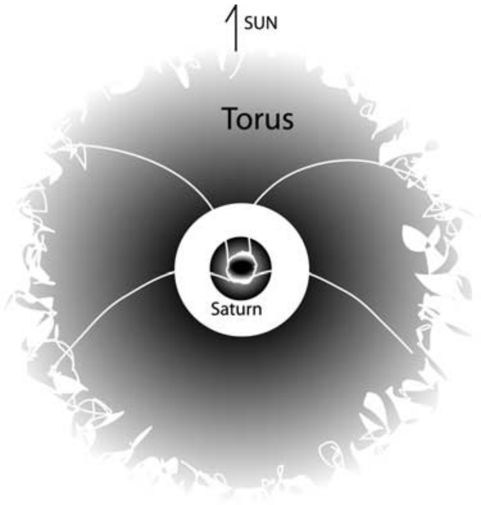

Figure 4. An illustration of Saturn's quiescent auroral system from a pole-ward vantage point, with the connection of auroral activity near 70° latitude to the outer edge of the ion plasma torus.

Their Figure 1a showed a quiescent aurora consisting of a partial thin ring of activity located between 68°- 72° latitude, this relatively extensive in local time. Nightside auroral activity could be clearly identified. Such morphology is also consistent with mapping to the outer edge of the torus that presumably surrounds the planet. Figure 4 illustrates the situation. However, during active periods, like in their Figure 1j, the auroral activity extended from ~73° to higher latitudes, beyond 85°, and was located near the dawn sector. Such observations during active periods suggest that the dawn sector of the magnetosphere between the torus outer edge and magnetopause is highly disturbed [*Cowley et al.*, 2005]. While the high-latitude active aurora appears to be correlated with solar wind activity [*Desch*, 1982; *Clarke et al.*, 2005; *Kurth et al.*, 2005], the quiescent aurora configuration could be driven by the torus region located well inside the magnetosphere. We note that during the SOI period, the SKR and aurora was considered relatively quiet [*Jackman et al.*, 2005], suggesting the aurora in a quiescent/torus-connected configuration.

[16] How then do we reconcile the Voyager and Cassini SKR source morphology, and integrate this morphology with the new knowledge of the aurora based on HST? We suggest that in quiescent conditions, the aurora has the form of a relatively weak "ring-of-fire" (active thin annulus) created by the torus outer edge. SKR emissions can then be observed both on the dayside and the nightside, but these emissions are substantially weaker and best observed by a spacecraft in relatively close proximity to the planet, like Cassini at SOI. In contrast, during active periods in the solar wind (pressure pulses), the aurora dawn sector becomes very intense, with high-latitude (~87°) active regions extending from noon to midnight [*Clarke et al.*, 2005] that beam intense SKR. Because of the nature of the flyby encounters (that make mostly distant observations), Voyager primarily sampled the most intense SKR during active periods, when the source region was strong and extended to its highest latitudes. Voyager's distance tended to act as a filter, emphasizing the high-latitude intense activity that was highly-correlated with solar wind pressure and deemphasizing the lower-latitude weaker emissions generated from the torus edge.

4. Conclusion

[17] The Cassini RPWS observations and our radio horizon analysis presented herein suggests a post-SOI SKR emission source close to midnight at relatively low latitudes; a source well away from the high latitude dayside cusp region derived by Voyager observations. This nightside source explains the surprising SKR event observed close to the planet between 05:00–09:00 SCET on DOY 183 of 2004. The SKR source located near local midnight, at southern latitudes between 72°–75° (L ~ 10–15), maps to the inner nightside magnetosphere in regions at the outer edge of the plasma torus surrounding the planet [*Richardson and Jurac*, 2004].

References

Calvert, W. (1981), The signature of auroral kilometric radiation on Isis 1 ionograms, *J. Geophys. Res.*, *86*, 76.

Clarke, J. T., et al. (2005), Morphological differences between Saturn's ultraviolet aurorae and those of Earth and Jupiter, *Nature*, *433*, 717.

Connerney, J. E. P., et al. (1984), Magnetic field models, in *Saturn*, edited by T. Gehrels and M. S. Matthews, Univ. of Ariz. Press, Tuscon.

Cowley, S. W. H., S. V. Badman, E. J. Bunce, J. T. Clarke, J.-C. Gérard, D. Grodent, C. M. Jackman, S. E. Milan, and T. K. Yeoman (2005), Reconnection in a rotation-dominated magnetosphere and its relation to Saturn's auroral dynamics, *J. Geophys. Res.*, *110*, A02201, doi:10.1029/2004JA010796.

Desch, M. D. (1982), Evidence for solar wind control of Saturn radio emission, *J. Geophys. Res.*, *87*, 4549.

Galopeau, P. (1992), Source location of the Saturnian kilometric radiation, in *Planetary Radio Emissions III*, edited by H. O. Rucker et. al., Austrian Acad. of Sci. Press, Vienna.

Gurnett, D. A., et al. (1981), Plasma waves near Saturn: Initial results from Voyager, *Science*, *212*, 235.

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

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

Huff, R. L., et al., Mapping of auroral kilometric radiation sources to the aurora (1988), *J. Geophys. Res.*, *93*, 11,445.

Jackman, C. M., et al. (2005), Interplanetary conditions and magnetospheric dynamics during the Cassini orbit insertion fly-through of Saturn's magnetosphere, *J. Geophys. Res.*, doi:10.1029/2005JA011054, in press.

Kaiser, M. L., and M. D. Desch (1982), Saturnian kilometric radiation: Source locations, *J. Geophys. Res.*, *87*, 4555.

Kaiser, M. L., et al. (1980), Voyager detection of nonthermal radio emission from Saturn, *Science*, *209*, 1238.

Kaiser, M. L., et al. (1984), Saturn as a radio source, in *Saturn*, edited by T. Gehrels and M. S. Matthews, Univ. of Ariz. Press, Tuscon.

Kurth, W. S., et al. (2005), An Earth-like correspondence between Saturn's auroral features and radio emission, *Nature*, *433*, 722.

Lecacheux, A., and F. Genova (1983), Source localization of Saturn kilometric radio emission, *J. Geophys. Res.*, *88*, 8993.

Richardson, J. D., and S. Jurac (2004), A self-consistent model of plasma and neutrals at Saturn: The ion tori, *Geophys. Res. Lett.*, *31*, L24803, doi:10.1029/2004GL020959.

Vogl, D. F., et al. (2004), In-flight calibration of the Cassini-Radio and Plasma Wave Science (RPWS) antenna system for direction-finding and polarization measurements, *J. Geophys. Res.*, *109*, A09S17, doi:10.1029/2003JA010261.

Wu, C. S., and L. C. Lee (1979), Theory of the terrestrial kilometric radiation, *Astrophys. J.*, *230*, 621.

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