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High spectral and temporal resolution observations of Saturn kilometric radiation

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[1] This paper presents the first high-resolution dynamic spectra of Saturn kilometric radiation acquired upon Cassini's approach and first orbits of Saturn. The emissions display upward and downward drifting features with bandwidths down to ~200 Hz and drift rates of a few kHz per second. At other times, the emissions are much more diffuse or continuous, showing little spectral structure on scales of 10 or 20 kHz. The fine structure is strikingly similar to Earth's auroral kilometric radiation (AKR) and Jovian auroral radio emissions in many respects. The dynamic spectral features provide insight into the highly nonlinear nature of the cyclotron maser instability believed to generate the emissions. We use ideas developed to explain the fine structures at Earth to suggest features and processes in the auroral acceleration region which may result in Saturn's fine structures. **Citation:** Kurth, W. S., G. B. Hospodarsky, D. A. Gurnett, B. Cecconi, P. Louarn, A. Lecacheux, P. Zarka, H. O. Rucker, M. Boudjada, and M. L. Kaiser (2005), High spectral and temporal resolution observations of Saturn kilometric radiation, *Geophys. Res. Lett.*, *32*, L20S07, doi:10.1029/2005GL022648.

1. Introduction

[2] Saturn's primary nonthermal radio component, Saturn kilometric radiation (SKR), was discovered in Voyager observations [*Kaiser et al.*, 1980]. Its name refers to the characteristic wavelength of the emission, given frequencies typically in the range of a few tens to several hundred kilohertz. The Voyager studies identified the source region at high latitudes in the morning to noon local time sector, possibly on field lines connecting to the magnetopause and in a region consistent with ultraviolet (UV) auroral emissions [*Kaiser et al.*, 1984; *Galopeau et al.*, 1995]. Early Cassini observations of the radio emissions in conjunction with Hubble Space Telescope observations of the UV aurora suggest that the radio emissions are tied to field lines threading bright auroral spots [*Kurth et al.*, 2005]. Based in large part on theory developed for AKR at Earth [cf. *Wu and Lee*, 1979; *Pritchett et al.*, 2002], it is assumed that Saturn's kilometric emissions are generated via the cyclotron maser instability near the electron cyclotron frequency f_{ce} at the source [*Galopeau et al.*, 1989].

[3] High resolution observations of the spectrum of AKR and its temporal variations [*Gurnett et al.*, 1979; *Gurnett and Anderson*, 1981; *Menietti et al.*, 1996; *Ergun et al.*, 1998] reveal a rich set of highly variable narrowband features that exhibit both upward and downward frequency drifts of the order of a few kilohertz per second, suggesting highly nonlinear interactions in the AKR source region. Fine structure has also been reported in Jovian radio emissions, most recently by *Lecacheux et al.* [2001], *Kurth et al.* [2001], and *Boudjada et al.* [2000].

[4] Given the importance of the electron cyclotron frequency in the cyclotron maser mechanism, the early investigators concluded that downward and upward drifting features were likely related to motions of the radiation sources up or down the field lines, respectively. *Gurnett and Anderson* [1981] pointed out that similarities between the radio emission spectrum and other cyclotron resonance emissions in the whistler mode suggested that there may be similar, underlying physical processes responsible for both. In particular, they suggested that electrostatic disturbances propagating near the ion acoustic speed might explain the drifting features in the kilometric radio spectrum. *Calvert* [1982] suggested that a mechanism involving feedback, similar to a laser, could explain the narrowband spectrum. *Pritchett et al.* [2002] argue that the feedback model is an unlikely explanation for the fine structure. *Pottelette et al.* [2001] suggest that electron or ion phase space holes propagating in the auroral current regions could act as tiny radiation sources within the source region and their small size and motions could account for the narrowband drifting features in AKR. *Menietti et al.* [1996] suggested that drifts of 'stripes' in Earth's radio spectrum to lower frequencies were consistent with the upward group velocity of electromagnetic ion cyclotron waves.

[5] The arrival of Cassini at Saturn opens a new chapter in the study of Saturn's kilometric radio emissions because of the advanced capabilities of the radio and plasma wave science (RPWS) instrument carried on the spacecraft [*Gurnett et al.*, 2004]. The observations in this paper utilize two 10-m electric monopoles in a balanced dipole configuration in conjunction with a wideband receiver with three different configurations. The wideband receiver can be used in the baseband with bandpasses of either 10 or 75 kHz, or in conjunction with the high frequency receiver, can down convert a 25-kHz

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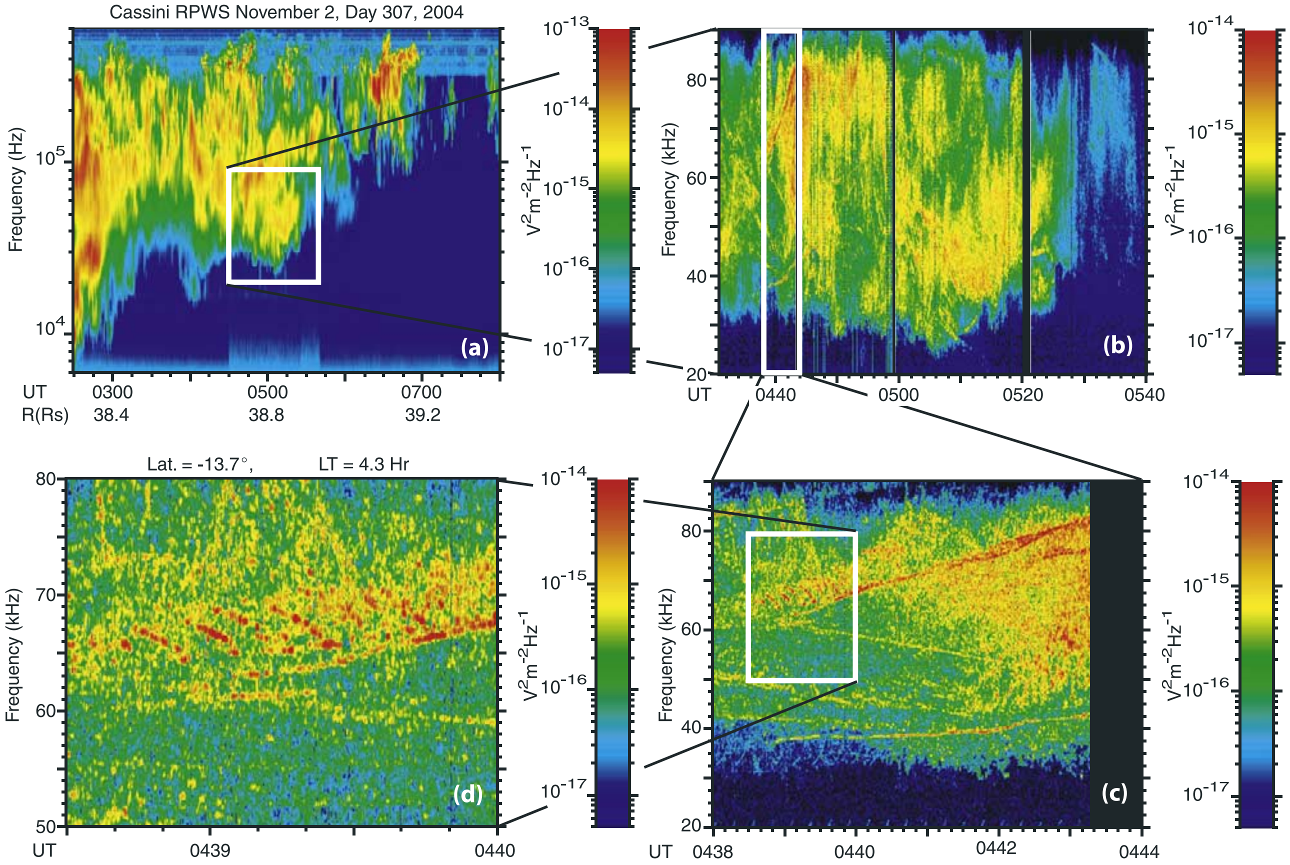

Figure 1. A composite of four SKR spectrograms of increasing spectral and temporal resolution. (a) Low rate frequency-time spectrogram showing the context of the wideband receiver observations (white box). (b) Wideband spectrogram showing the nearly 1 hr, 10 min set of observations in the 75-kHz mode. (c) Temporal expansion of data shown in panel b. (d) Detailed spectrogram of a 90-second interval highlighted in panel c. The resolution is approximately 125 msec by 100 Hz in this panel.

bandwidth tuned to frequencies between 125 kHz and 16 MHz. This paper utilizes the 75-kHz baseband and a down converted band centered on 325 kHz.

2. Observations

[6] Cassini acquires nearly continuous low rate observations of the electric field spectrum from 1 Hz to 16 MHz with temporal resolutions of typically 16 or 32 seconds and with moderate spectral resolution ($\Delta f/f = 5\%$). Using these data, Cassini first observed SKR on April 9, 2002 at a distance of some 2.5 AU from Saturn. Because of the high data rates required for wideband observations, these are acquired only occasionally and for short intervals, for example, a minute or two every few hours and must be shared with other objectives. Since 9 April 2002, approximately 36 hours of 325-kHz band wideband data and approximately 311 hours of 75-kHz baseband mode data have been acquired, although only a small percentage of these observations were obtained when SKR was present. This paper is based on a preliminary survey of these data. It should be noted that because of Saturn's seasonal tilt and Cassini's approach trajectory as well as the inclination of the early orbits, the majority of observations of SKR to date are of the southern hemisphere source. We do not expect fundamental differences between emissions from the two hemispheres, however, the slight northerly offset of the magnetic moment of Saturn leads to a somewhat higher frequency extent for the northern emission.

[7] Figure 1 includes low-rate and 75-kHz wideband data during a rare occasion when approximately 1 hour, 10 minutes of wideband data were available. For this time, 2048 consecutive 8-bit waveform samples were acquired at a rate of 222,222 s^{-1} approximately every eighth of a second. This represents a ~9.2 msec waveform series every 125 msec, for a duty cycle of a little more than 7%. The data are losslessly compressed on board to minimize the required data volume and then decompressed as part of the ground processing. Typically, to avoid windowing effects, each 2048-sample series is Fourier transformed independently and the resulting spectra are used to build frequency-time spectrograms. Of course, the waveforms can also be viewed and analyzed in the time domain, as well. With this set of processing parameters, the spectral resolution is about 100 Hz.

[8] To show the rich nature of this data set, Figure 1 shows four different portions of the SKR spectrum increasing in resolution clockwise from the upper left panel. The lowest resolution spectrogram (a) uses the low-rate spectral information to show the context of the wideband measurements. This particular radio emission extends from below 10 kHz at the beginning of the displayed interval to nearly

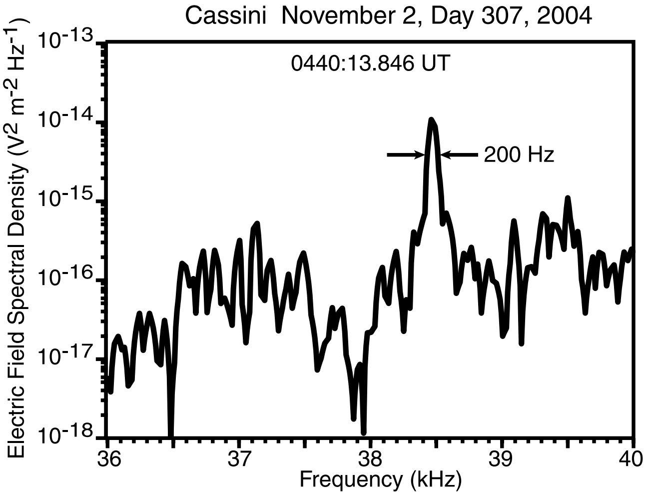

Figure 2. Detail of a single spectrum showing the narrowband feature at 38.5 kHz seen in Figure 1c. The spectral resolution is about 25 Hz, so the narrowband emission is resolved and has a bandwidth of about 200 Hz.

600 kHz. The constant frequency narrowband emissions near the top of this spectrogram are due to interference from various power supplies on the spacecraft. The white square defines the time and spectral range for the first wideband spectrogram (b) covering the entire wideband data interval from below the radio emission low frequency limit to about 90 kHz. The roll off of the antialiasing filter is rather gradual, hence, there is significant response above the 75-kHz 3-dB point of the filter. The data in this spectrogram are oversampled relative to the time and frequency range of the spectrogram, hence, the resolution is intermediate between the low-resolution data and that ultimately achievable with these measurements. Nevertheless, strikingly narrowband features, sharp spectral boundaries, and drifting features are found in several different frequency-time regions of this display. These are accompanied by more diffuse, continuum-like components to the spectrum.

[9] Figure 1c begins to show some of the rich fine structure in SKR. This five-minute interval shows narrowband emissions that drift upwards, downwards, and remain nearly constant in frequency over time spans of several minutes. Further, the spectrogram shows somewhat mottled or chaotic spectral forms as well as highly organized narrowband tones showing similar drift rates and almost a periodic nature. One type of this latter phenomenon not shown here appears to be similar to the ‘stripes’ reported by *Menietti et al.* [1996] at Earth. These are downward drifting narrowband emission elements with drift rates of a few kHz/s. At Saturn, these are often seen in clusters of large numbers of elements, all with approximately the same drift rate. Our impression is that these are observed near the lower frequency end of the Saturn kilometric frequency range. This impression may be biased by data selection effects.

[10] The final spectrogram (d) shows some of the finest spectral features of SKR at the full resolution of this acquisition mode. The series of downward drifting tones have drift rates of about −1 kHz/s. The longer narrowband emission below them is drifting upwards at a rate of about 100 Hz/s. This series of organized drifting tones and their association with a more regular narrowband tone is reminiscent of ground-based observations of millisecond bursts in Jovian decametric radiation [*Boudjada et al.*, 2000] although the drift rates for the Jovian S-bursts are drastically faster than the Saturnian emissions shown here.

[11] Some of these narrow features may be unresolved. To pursue this further, we examined the narrowband feature near 38.5 kHz near 0440 UT in panel (c) by combining four consecutive waveform series (a total of 8192 samples) to increase the spectral resolution to about 25 Hz. The resulting spectrum is shown in Figure 2. While there may be some spurious windowing products because the four waveform series are discontinuous in time, it is apparent that this narrowband feature has a bandwidth of about 200 Hz or about 0.5%. This is in the same range as bandwidths reported for AKR [*Ergun et al.*, 1998] but not as narrow as the 5 Hz inferred from interferometric measurements of the terrestrial emissions [*Baumback and Calvert*, 1987]. The 0.5% bandwidth is consistent with the expected natural bandwidth of the maser process which is given by $f_{ce}E/mc^2$ where E is the typical energy of the electrons [*Louarn and LeQuéau*, 1996]. This suggests the electrons in the Saturn kilometric source have energies of about 2–4 keV, comparable to those observed in the terrestrial kilometric source.

[12] Figure 3 shows a truly remarkable frequency-time spectrogram using the 325-kHz down-conversion capability. Near the bottom of the spectrum is a narrowband emission with a (probably unresolved) bandwidth of less than 1 kHz which first drifts upwards and then downwards in frequency. Apparently triggered by this spectral feature is a series of three similarly narrowband emissions which drift upwards at rates of about 10 kHz/s. The time between the apparently triggered emissions is 7–8 seconds; there is some evidence at lower frequencies that a fourth emission was in the process of being generated just before the end of this observation.

[13] As unique as the observations in Figure 3 appear, a very similar set of observations has been published by *Gurnett and Anderson* [1981] showing what appears to be a series of triggered AKR emissions in ISEE 1 wideband

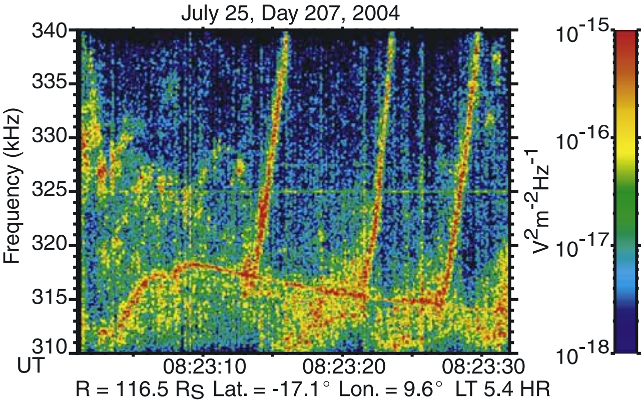

Figure 3. A remarkable frequency-time spectrogram centered at 325 kHz showing a series of rapidly rising tones (∼10 kHz/s) evidently triggered by a narrowband tone with a slight negative drift.

data. *Boudjada et al.* [2000] show what appear to be similar emissions from Jupiter.

3. Discussion and Conclusions

[14] This paper presents the first high resolution dynamic spectra of SKR. The Saturn emissions show a rich variety of fine structure similar to that of AKR at Earth and auroral radio emissions at Jupiter. Some of the patterns in the fine structure are nearly identical to those found at Earth. These data indicate that the physical processes at Saturn may be similar to those at Earth and Jupiter. The similarity demonstrates the ubiquity of the microphysics of the cyclotron maser instability despite significant differences in magnetospheric configurations, energy sources, and plasma sources. We have shown just a few examples of the Saturnian emissions which exhibit a wide range of spectral and temporal features. These range from rather featureless spectra with little variation on time scales of minutes to narrowband tones with bandwidths as small as 200 Hz, less than one percent of the center frequency. The narrowband tones can be seen to drift both to higher and lower frequencies at rates from less than 1 kHz/s to as much as 10 kHz/s. Many spectra have virtually chaotic spectral variations. There is even evidence of triggered emissions, similar to those reported in AKR.

[15] We have relied on existing work on the fine structure of AKR to point out some of the source processes which may be responsible for the observed spectral features. First, the very small bandwidths of some of the features suggest a highly nonlinear generation mechanism, multiple small radio sources, and/or extremely narrow beaming or other propagation properties. Second, the drift rates of the narrowband emissions likely reflect small emitting centers moving up or down the source magnetic field. For the drifts reported herein, the speeds implied range up to 1000 to 2000 km/s. These are similar to, for example, speeds associated with the 'stripes' estimated by *Menietti et al.* [1996] and similar to the group velocity of electromagnetic ion cyclotron waves that are often found in the terrestrial auroral region. Further, early Cassini observations reveal the existence of low-latitude electron and ion phase space holes at the magnetopause and in the magnetosphere, hence, it is likely that such phenomena also travel along field lines in Saturn's auroral current regions, as at Earth. Near the end of its prime mission in 2008 Cassini will likely traverse auroral field lines at relatively small radial distances (<5 Saturn radii), so it may be possible to relate some of the observed fine structure in the kilometric radio emissions with phenomena found in or near the acceleration region.

[16] As pointed out by *Pritchett et al.* [2002], there is no consensus theory for the more highly studied terrestrial kilometric radiation fine structure. Given this situation and no in situ observations in Saturn's source region at present, it is premature to expect a complete theoretical understanding of Saturn's fine structure. But, ongoing analyses of the Saturnian emissions and the potential of in situ observations offer the possibility of a more complete theoretical description of the cyclotron maser instability in planetary auroral regions, in general.

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