

SATURN RADIO WAVES

W. S. Kurth* and P. Zarka†

Abstract

This paper is designed to summarize what is known about Saturnian radio emissions, relying almost entirely on Voyager observations from 1980 and 1981 and some remote observations by Ulysses. It also outlines the major radio astronomy objectives for the Cassini radio and plasma wave science (RPWS) investigation. The three primary known radio emission types at Saturn include Saturn kilometric radiation (SKR), an auroral radio emission similar to auroral kilometric radiation at Earth and deca-, hecto-, and broadband kilometric radiation at Jupiter; low-frequency narrowband and possibly related trapped continuum radiation also similar to emissions seen at Earth and Jupiter; and Saturn electrostatic discharges originating from lightning in Saturn's atmosphere. To set the stage for the Cassini mission between 2004 and 2008, we'll outline a number of open issues and objectives for the Cassini RPWS investigation. Given the capabilities and excellent sensitivity of the Cassini RPWS, we anticipate detection of Saturnian radio emissions well before the spacecraft arrives in 2004 and the beginning of studies designed to address the questions outlined herein and more.

1 Introduction

The Cassini Orbiter is set to begin orbiting Saturn on July 1, 2004, for a four-year tour of the Saturnian system including the planet and its atmosphere, rings, icy satellites, Titan, and the magnetosphere. The Huygens probe is carried by Cassini for in situ studies of Titan's atmosphere and surface. One of the instruments included in the Cassini Orbiter's payload is a radio and plasma wave science (RPWS) investigation which will, among a number of other studies, be used to complete in-depth studies of Saturn's radio emissions [Gurnett et al., 2001b]. This review is to survey our current state of knowledge of Saturn radio emissions and to highlight a number of issues and questions to be addressed by the RPWS. We discuss Saturn kilometric radiation (SKR), low-frequency narrowband and possibly related trapped continuum radiation, and Saturn electrostatic discharges. We specifically do not attempt to address other objectives of the RPWS investigation

*Dept. of Physics and Astronomy, University of Iowa, Iowa City, IA 52242, USA

†DESPA, CNRS/Observatoire de Paris, F-92195 Meudon, France

including plasma waves, thermal plasma measurements, and measurements of dust in the Saturnian system here. However, these are covered by Gurnett et al. [2001b].

The Cassini RPWS is a highly capable instrument, designed to measure the spectrum of radio and plasma waves from 1 Hz to 16 MHz with a set of highly capable receivers. Details of the instrumentation are given in Gurnett et al. [2001b]. However, for the purposes of this review, we'll simply mention that the high-frequency receiver built at the Observatoire de Paris in Meudon will be able to determine all four Stokes parameters and the directions of arrival of radio emissions in the frequency range above 3.6 kHz. This receiver has a great deal of flexibility enabling special focus in either temporal or spectral resolution on particular regions of the spectrum. Furthermore, the high-frequency receiver combined with the wideband receiver built at the University of Iowa can provide high spectral and temporal resolutions in the baseband up to 75 kHz and within a 25-kHz bandpass tunable from 125 kHz to 16 MHz. The radio astronomy capabilities of the instrument have been shown to be exceptional based on performance during the Venus, Earth and Jupiter flybys [Gurnett et al., 2001c; Kaiser et al., 2000; Kurth et al., 2001a; Kurth et al., 2001b; Lecacheux et al., 2001a; Kaiser et al., 2001; Vogl et al., 2001a; and Gurnett et al., 2001a].

2 Present state of knowledge of Saturn radio emissions

Our present state of knowledge of Saturn radio emissions is based largely on the Voyager planetary radio astronomy and plasma wave investigations [Warwick et al., 1981, 1982; Gurnett et al., 1981a; Scarf et al., 1982] and the Ulysses unified radio and plasma wave investigation [Lecacheux et al., 1997] which has made important contributions despite its large distance from the planet. Reviews of relevance to this paper include Kaiser et al. [1984], Kaiser [1989], and Zarka [1998, 2000].

2.1 Saturn Kilometric Radiation

2.1.1 General characteristics

By far the most important Saturnian radio emission is Saturn kilometric radiation extending from below 20 kHz to as high as 1.2 MHz with a broad peak in the range of 100 to 400 kHz. The emission is typically bursty and displays arc-like structures and bands, although these are not as well organized as those observed in the Jovian decametric radiation. Figure 1 shows the average SKR spectrum scaled to 1 AU in comparison to the spectra of the primary radio emissions of the other planets. Saturn is second in intensity only to Jupiter, but its spectral range is very similar to that of the remaining magnetized planets. Figure 2 shows an example frequency-time spectrogram obtained by the Voyager planetary radio astronomy (PRA) instrument which shows the arc-like structures and burstiness of these emissions. Galopeau et al. [1989] have modeled the SKR spectrum based on the cyclotron maser instability and models for the conditions in the source region (magnetic field, cold plasma density, and the energetic particles which

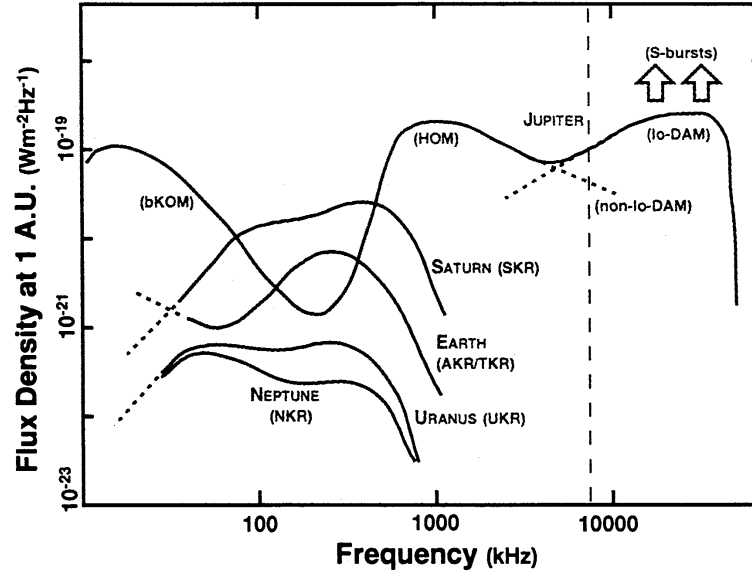


Figure 1: The Saturn radio spectrum compared to those from Earth, Jupiter, Uranus, and Neptune [Zarka, 1998].

radiate) and arrive at a theoretical spectrum which is in very good agreement with that which is observed. That the model spectral densities are up to an order of magnitude more than the most intense observed suggests that the emission is never more than marginally saturated by nonlinear processes. Zarka [1992a] extended this work by deriving the variations of density and the energy of precipitating electrons in the SKR source region from parametric fits of the SKR spectra.

Several studies of the SKR source region exist [Kaiser et al., 1981; Kaiser and Desch, 1982; and Lecacheux and Genova, 1983], but the most recent analysis based on the Voyager PRA data by Galopeau et al. [1995] uses variations in the polarization along the Voyager 1 and 2 trajectories. Figure 3 summarizes the conjugate source locations derived in this study. These locations are near 80° latitude in the local time (LT) range of 1200–1300 but include extensions to lower latitude (to about 60° latitude) near 0900 LT. The deduced beaming is along the walls of a hollow cone with a half-apex angle of 60° – 90° . The local time of the low-latitude extension is similar to the location of a Kelvin–Helmholtz instability observed on the dayside magnetopause by Lepping et al. [1981b], leading Galopeau et al. to suggest that the K-H instability could be the source of precipitating electrons driving the generation of the SKR.

Saturn kilometric radiation is 100% circularly polarized and is propagating in the extraordinary mode, hence, is observed to be right-hand polarized from the northern source and left-hand from the southern source [Kaiser et al., 1980, 1984]. This information plus the aforementioned conclusive evidence of source regions at high latitudes near the planet lead directly to the conclusion that SKR is generated via the cyclotron maser instability [Wu and Lee, 1979] as part of the same process which generates auroras at Saturn. The

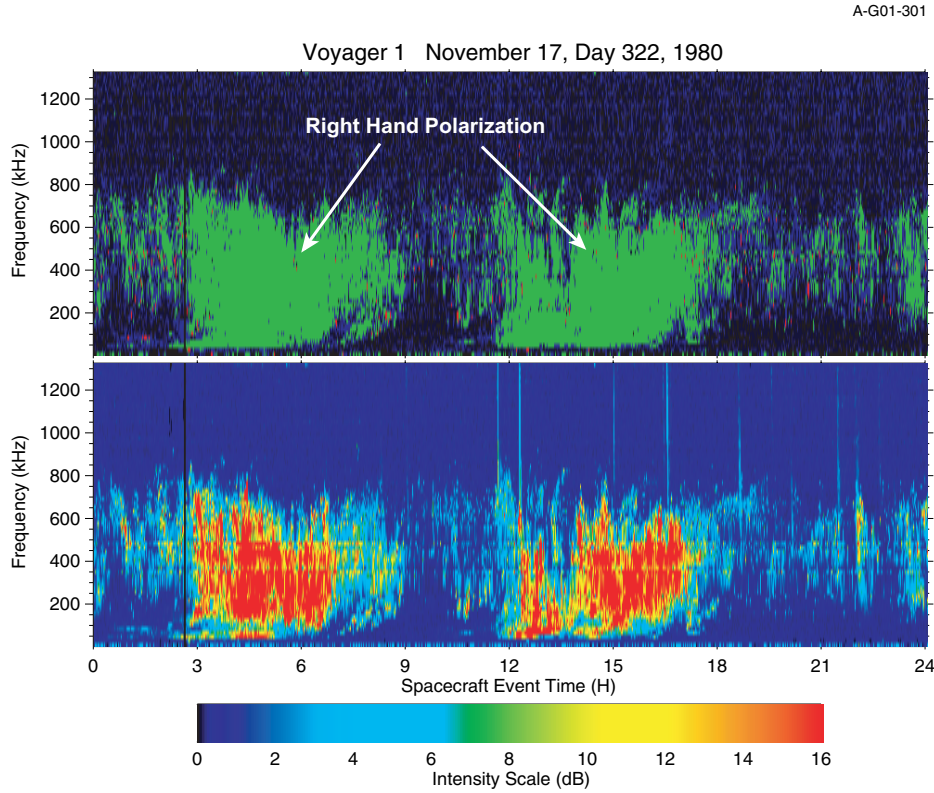


Figure 2: An example of SKR from Voyager 1. The bottom panel shows the intensity of SKR as a function of frequency and time for a 24-hour interval. Notice the arc-like structures visible in this presentation. The upper panel shows the sense of polarization. Here the waves are predominantly right hand (in the radio astronomical sense) and correspond to the right-hand extraordinary mode (in the plasma sense).

connection between the SKR source and auroras on Saturn has been shown definitively by the combination of SKR source localization by Galopeau et al. [1995] and auroral observations by Gérard et al. [1995] and Trauger et al. [1998] using UV observations of the aurora with the Hubble Space Telescope.

2.1.2 Temporal variations

As described below, Voyager observations of Saturn kilometric radiation were used to determine the radio rotation period of Saturn using the fact that the radio emissions exhibited a strong modulation at just less than 10 h, 40 min period. Given the Pioneer 11 [Smith et al., 1980] and Voyager 1 and 2 measurements of Saturn’s magnetic field, this strong rotational modulation quickly became a puzzle, however, since the magnetic field models, e.g. the Z3 model of Connerney et al. [1984], were axisymmetric. Both terrestrial

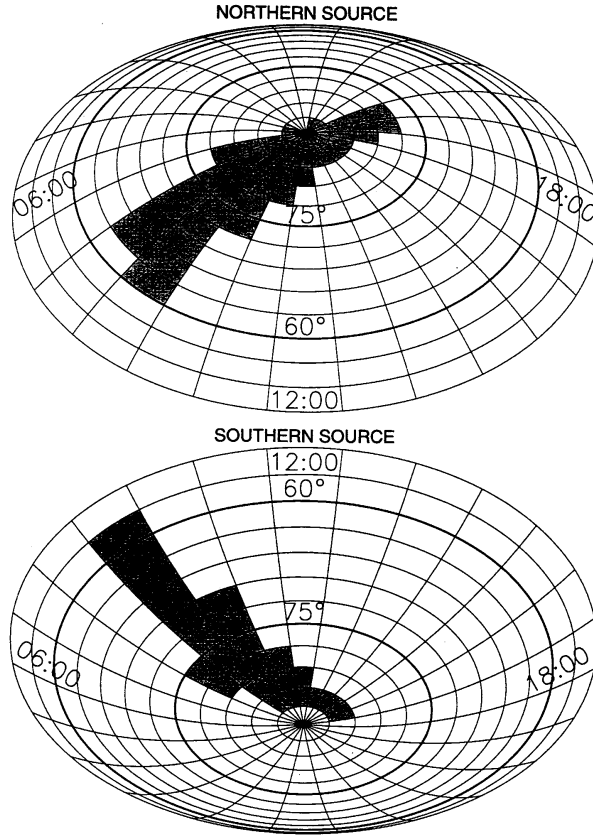


Figure 3: A summary of SKR source locations [Galopeau et al., 1995].

auroral kilometric radiation and the Jovian radio emissions demonstrate strong rotational modulation, but both of these planets' magnetic moments are tilted approximately 10° from the rotation axis and in the case of Jupiter is offset from the rotational axis. Hence, the modulation is not surprising. The axisymmetric field at Saturn, however, provides no obvious means to modulate the radio emissions.

Galopeau et al. [1991] and Galopeau and Zarka [1992a] suggested that a magnetic anomaly (or asymmetry) in the high-order terms of Saturn's field might explain the apparent paradox. Since the high-order terms only involve fields which can be measured very close to the planet, it is possible that an asymmetry could exist in these terms and the flyby spacecraft would not be sensitive to it. Galopeau et al. [1991] and Galopeau and Zarka [1992a] demonstrated this concept by modifying the high-order terms in such a way so as to match the high-frequency limit variation of the SKR spectrum as a function of longitude. Connerney and Desch [1992] commented that this expansion is inconsistent with the spacecraft measurements, hence, the model could not be correct. Ladreiter et al. [1994a] have developed a similar field model to that of Galopeau et al., but have constrained it to also match the observed field over the limited geometry afforded by the flybys. Using techniques similar to Galopeau et al. [1995] and Ladreiter et al. [1994a]

plus the RPWS direction-finding capability, significant progress should be possible on further characterizing the magnetic anomaly. Of course, more comprehensive magnetic field measurements close to Saturn over a broad distribution of longitudes and latitudes will also be useful, provided they are made close enough to the SKR source. The Cassini magnetometer (MAG) investigation [Dougherty et al., 2001] has such measurements at very high priority for the mission. And, a greater understanding of SKR should come with Cassini measurements on auroral field lines near or perhaps even in the source region.

As mentioned above, Voyager observations provided the first ‘definitive’ measurement of the radio period of Saturn [Desch and Kaiser, 1981]. For the gas giants, knowing the radio rotation period has been considered very important from a planetary perspective because, ostensibly, this period is tied to the rotation of the core of the planet that supports the magnetic field. Having such a basis allows for a basic period upon which to compare the rotation period in clouds at various latitudes in order to compute wind speeds, for example. Therefore, as a consequence of determining this period to be 10 h, 39 min, 24 ± 7 s (10.657 h), Desch and Kaiser were able to determine a Saturnian longitude system (SLS) defined by

$$\lambda_{SLS} = 810.76(t - t_0 - 3.86 \times 10^{-11}D) - R \quad (1)$$

where t is the decimal time in days, t_0 = January 1.0, 1980, D is the observer–Saturn distance in kilometers, and R is the observer right ascension (epoch 1980) in degrees. Since λ_{SLS} increases with time, it is a westward longitude. Other determinations by Carr et al. [1981] and Godfrey [1990] arrive at slightly different periods, but all within the Desch and Kaiser error bar. The International Astronomical Union/International Association of Geodesy/Committee on Space Programs and Research Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites [Davies et al., 1996] have defined the ‘official’ sidereal period as 10 h, 39 min, 22.4 s (10.656222 h) corresponding to an angular velocity of 810.7939024°/d.

However, because of its very good sensitivity, the Ulysses unified radio and plasma wave instrument has the capability of detecting Saturn from very large distances, hence, Galopeau and Lecacheux [2000] have been able to measure the rotation rate based on a very long time scale (823 days compared to the 267-day span used by Desch and Kaiser [1981]). Their very surprising result is a period which is as much as 1% longer than that obtained by the Voyager measurements and which has statistically significant variations on time scales of a year. This obviously presents a problem for the interpretation of the radio period as that of the planetary core rotation period, not to mention the difficulties which arise in tracking a consistent longitude over periods of a month or more.

Galopeau and Lecacheux [2000] suggest that the variation may be due to the connection of the SKR source to the Kelvin–Helmholtz instability on the morning flank of the magnetopause [Galopeau et al., 1995]. In particular, they suggest that the motion of the source zone on the magnetopause can induce variations of the order a few percent in the apparent radio period. However, they further conclude that one might expect that such drifts should cancel out over long periods of time.

More recently, Zarka and Cecconi [2001] have pointed out that the Solar wind velocity is commonly observed to have an asymmetric sawtooth form, and show that the convolution of this type of motion of the source region at the magnetopause with the underlying planetary rotation can, indeed, result in an average periodicity which does not average to the planetary rotation period. In fact, they point out that a detailed analysis of the periodogram would show a peak at both the rotation period and a secondary peak with a somewhat longer period. These two peaks would form a single one at lower resolution at a somewhat larger period than that of the rotation.

Another issue dealing with the periodicity of the Saturn kilometric radiation is the reports of an apparent control of the emission by Dione [Desch and Kaiser, 1981; Kurth et al., 1981b; Warwick et al., 1981, 1982; Gurnett et al., 1981a; Genova et al., 1983]. This effect manifested itself during the Voyager 1 flyby in the form of missing SKR episodes when Dione was at a particular phase in its orbit, specifically when the wispy terrain was in the sunlit hemisphere, suggesting that enhanced plasma production from sputtering and photoionization or electron impact might briefly block radio emissions from the equatorial region. However, the so-called Dione effect was transient, and when it did re-occur, the phase was different and in some cases the period was not consistent with the orbital period of Dione [Genova et al., 1983]. Genova et al. generally conclude that these types of variations in the SKR spectrum have a more complex explanation involving more than Dione including variations in the SKR source. Zarka et al. [2001b] argue on the basis of a generalized Bode's law for Solar system radio sources that Dione has a too small cross section with Saturn's magnetic field to influence SKR in any significant way. Furthermore, should Cassini, on the basis of longer term measurements, demonstrate that the effect is truly there, then it would imply a significantly larger cross section for Dione (of order 10) due, perhaps, to a substantial intrinsic magnetic field or an extended exosphere [Zarka et al., 2001b]. The extended tour of Cassini in Saturn orbit will provide the length of observations required to establish the existence (or not) of the control of SKR by Dione (or any other of the satellites, for that matter). Furthermore, should an effect be found, the Cassini data can determine the nature of the phase shift observed by Voyager as well as investigate the magnetospheric interaction with Dione and the other satellites such that a model for the interaction can be developed.

Other temporal changes in the Saturnian kilometric radiation are due to variations in the Solar wind as illustrated in Figure 4. These were first reported by Desch [1982] and studied further by Desch and Rucker [1983]. In particular, there is a strong positive correlation between the SKR intensity and the Solar wind ram pressure. This correlation was demonstrated in an extraordinary way during brief immersions of Saturn in the distant Jovian magnetotail, which served to sharply reduce the plasma flux impinging on Saturn's magnetosphere [Desch, 1983]. This correlation with Solar wind input will serve to be very important to the Cassini studies of the Saturnian magnetosphere in general. Given that there will not be a Solar wind monitor at Saturn, Cassini will be unable to directly measure the Solar wind conditions when it is situated within the magnetosphere. Likewise, Cassini will not have in situ measurements of the magnetosphere when it is near apoapsis in its orbit while it is measuring the Solar wind. The remotely sensed SKR emission intensity offers one tool for measuring the state of the magnetosphere even when it is in the Solar wind. (Energetic neutral atoms observed by the Cassini Magnetospheric imaging

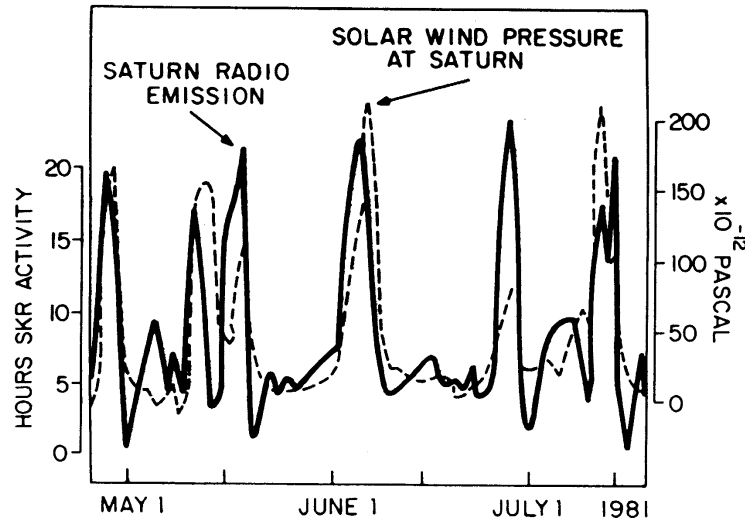


Figure 4: The correlation between Solar wind ram pressure and SKR intensity. [Figure from "Saturn as a Radio Source," by M. L. Kaiser et al., in *Saturn*, edited by T. Gehrels and M. Matthews. Copyright © 1984. The Arizona Board of Regents. Reprinted by permission of the University of Arizona Press.]

instrument (MIMI) [Krimigis et al., 2001] and visible and UV imaging of auroral emissions by the imaging science instrument (ISS) [Porco et al., 2001] and ultraviolet imaging spectrometer instrument (UVIS) [Esposito et al., 2001], respectively will give additional information.) Similar measurements of the terrestrial auroral kilometric radiation have been shown to be effective proxies for the auroral electrojet index and other information on magnetic activity at Earth [Voots et al., 1977; Murata et al., 1997; Kurth et al., 1998; Kurth et al., 2001a; Khan et al., 2001]. Most recently Gurnett et al. [2001a] have used observations of Jovian hectometric radiation to demonstrate the effect of interplanetary shocks on the Jovian magnetosphere and to demonstrate the importance of Solar wind variations on magnetospheric dynamics at Jupiter. (Numerous studies had previously explored correlations between the Solar wind and various Jovian radio emissions; see the review by Zarka [1998] and references therein.) Hence, it will be important to build on the Voyager studies of the correlation between the Solar wind and SKR in order to use the SKR intensity as an indicator of Solar wind variations while Cassini is within the magnetosphere. Such correlations will be critical to understanding the role of the Solar wind in the dynamics of the Saturnian magnetosphere, should they be discovered by Cassini.

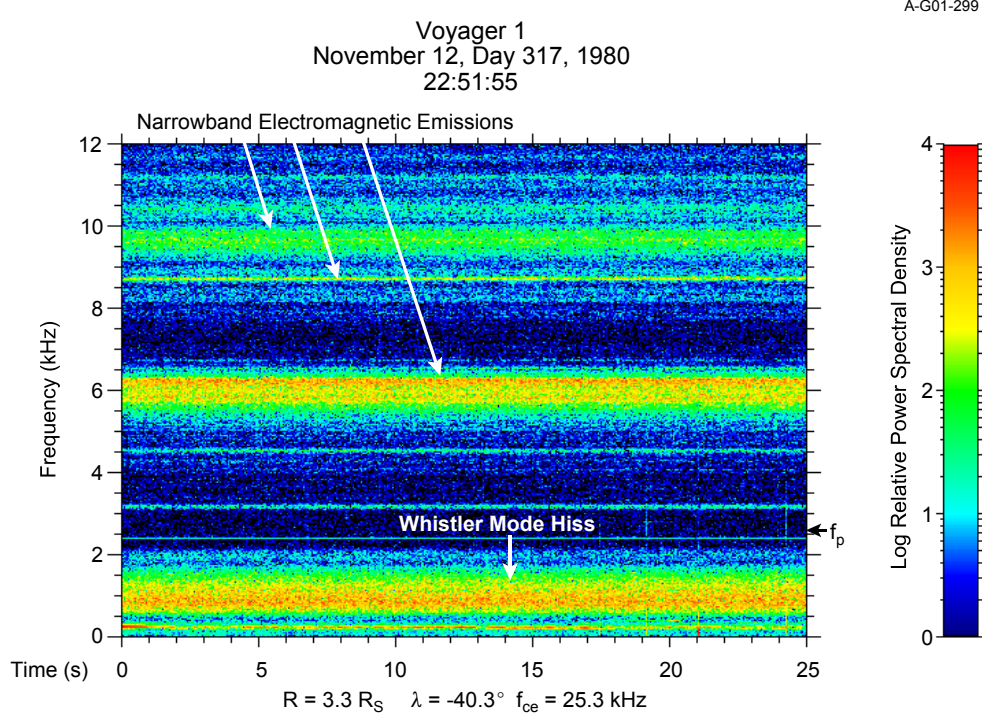


Figure 5: An example of narrowband electromagnetic emissions observed by Voyager 1.

2.2 Low frequency emissions

2.2.1 Narrowband electromagnetic bands

Gurnett et al. [1981b] reported on the existence of a complex set of narrowband electromagnetic emissions in the frequency range of 3 to 30 kHz at Saturn (see Figure 5). These emissions are reminiscent of escaping continuum radiation at Earth [Kurth et al., 1981a] and Jupiter [Gurnett et al., 1983]. In all three cases, it is generally believed that such emissions are generated via mode conversion from electrostatic upper hybrid waves on density gradients near the inner magnetosphere. In the case of Saturn, Gurnett et al. [1981b] pointed out that the spacing of the narrowband radio emissions was in some cases similar to the electron cyclotron frequencies near the orbits of Tethys, Dione, and Rhea, suggesting that the source of the emissions could be related to the magnetospheric interaction with these moons. In fact, the banded radio emissions which originate at Ganymede's magnetosphere [Gurnett et al., 1996; Kurth et al., 1997a] are perhaps Ganymede's counterparts to these emissions, if indeed they are related to an unusual situation near these Saturnian moons, including the production of plasma or even the possibility of a satellite

magnetosphere. While the band spacing is certainly suggestive of a source at the orbits of these moons, it is not conclusive. Hence, a primary objective for Cassini is to determine the source of the radio emissions, and should they be generated as a result of the magnetospheric interaction between the magnetosphere and Tethys, Dione, or Rhea, then to understand that interaction and how it might result in the generation of radio emissions.

2.2.2 Continuum radiation

At Earth, the narrowband escaping continuum radiation is understood to simply be an extension of the non-thermal continuum radiation which, at lower frequencies, is trapped within the magnetospheric cavity, or trapped continuum radiation [Gurnett, 1975]. In fact, at Saturn, there is also evidence of trapped continuum radiation as shown in Figure 6 [Kurth et al., 1982]. These emissions are weak and diffuse, extending upward from the presumed local electron plasma frequency in Saturn's magnetosphere in the range of a few hundred Hz to a few kHz. Hence, these waves are important if only because they provide the opportunity to accurately determine the electron density from their low-frequency cutoff. An issue, however, is whether they are, like those at Earth, directly related to the narrowband emissions discussed above, or a distinctly different emission. The answer is largely related to whether the moons are the source of the narrowband emissions or not since it is unlikely that plasma frequency in the vicinity of the orbits of the icy satellites is as low as a few hundred Hz.

2.3 Radio emissions associated with lightning

2.3.1 Saturn Electrostatic Discharges

Other prominent radio emissions observed by the Voyager planetary radio astronomy investigation near Saturn are short, broadband bursts called Saturn electrostatic discharges (SED) [Warwick et al., 1981, 1982; Zarka and Pedersen, 1983]. These bursts have a mean duration of 55 ms but range from less than 30 ms to 450 ms. The spectrum is basically flat from 1.2–40 MHz but the low-frequency cutoff is variable. The average power per unit frequency in the bursts ran from $\sim 60 \text{ W Hz}^{-1}$ during the Voyager 1 encounter to about 6 W Hz^{-1} during the Voyager 2 encounter. Given that the bandwidth is at least 40 MHz, the average total power is between about 2×10^8 and $2 \times 10^9 \text{ W}$ but can exceed 10^{10} W in strong events.

The SED were observed episodically by the two Voyager spacecraft while they were in the near vicinity of Saturn. By using the occurrence of SED as a function of time and frequency, Kaiser et al. [1983] were able to demonstrate that most of the bursts originated in the Saturnian atmosphere from presumably a storm which extended some 60° in longitude but less than 4° in latitude. Burns et al. [1983] also concluded that lightning could be the source of the SED. In this model the variability in the low-frequency cutoff of the bursts is due to the ionospheric cutoff between the source and the observer, a feature which makes the study of this cutoff an important method for sounding the ionospheric density over a wide range of locations [Zarka, 1985a]. In order to carry this out, however, it is necessary

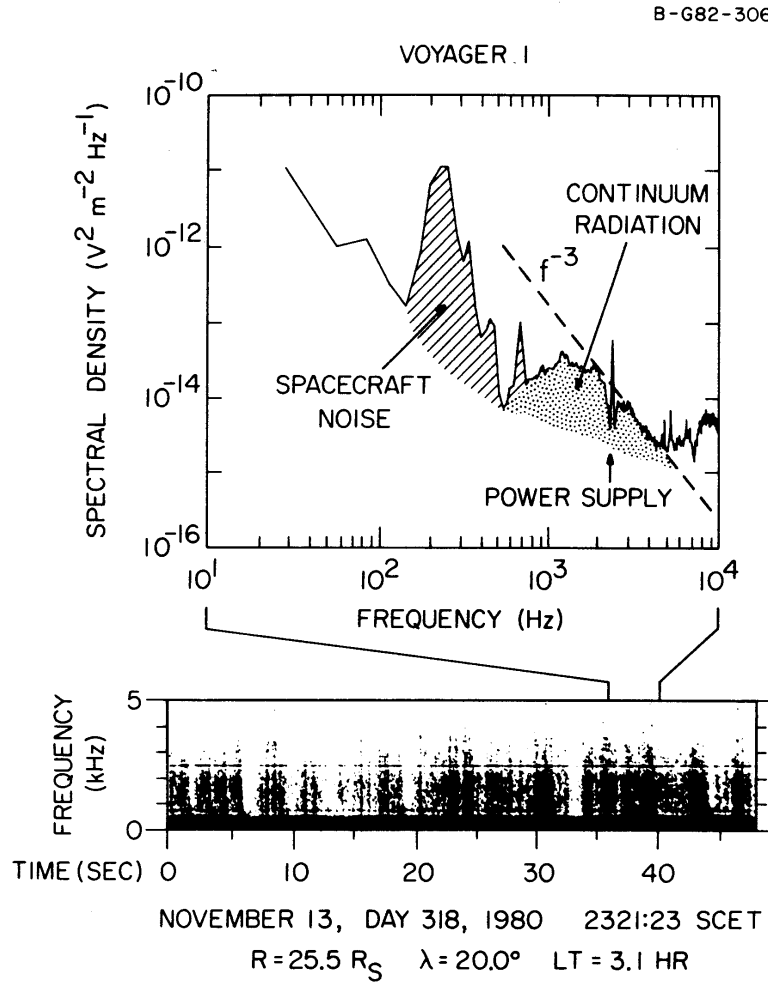


Figure 6: Trapped non-thermal continuum radiation at Saturn [Kurth et al., 1982].

to determine the location of the source on the planet [Zarka, 1985b]. Cassini offers the possibility to do this for individual bursts using its direction-finding capability.

There remains some controversy over atmospheric lightning as the source for the SED [c.f., Hunten, 1985]. Cassini should be able to investigate such concerns and, with its direction-finding capabilities, clearly identify the source of SED. As to the question of lightning, in general, Voyager did not find clear evidence of lightning whistlers. This is possibly due to Voyager not crossing near field lines connected to lightning in the atmosphere or to the fact that dust impacts close to Saturn tended to mask other naturally occurring phenomena. Cassini's orbital tour should carry the spacecraft to all but the smallest L-shells and at high enough latitudes where dust impacts should not be an issue. The detection of lightning whistlers would provide additional information of the existence of lightning and near simultaneous detection of whistlers and direction-finding of SED should further tie the SED to lightning.

2.3.2 *Lightning at Titan?*

Voyager 1 planetary radio astronomy measurements placed an upper limit on the energy release (per flash) of lightning on Titan at 10^6 J assuming an occurrence rate similar to that on Earth. This limit was based on the brief Voyager 1 flyby [Desch and Kaiser, 1990]. Due to its superior sensitivity and the opportunity to make more than 40 very close flybys, Cassini has a better opportunity to observe lightning on Titan which is either weak, infrequent, or both. Lammer et al. [2001] discuss the possibility for lightning in Titan's atmosphere and the prospects for its detection by Cassini. The RPWS would be a key instrument for its detection via radio emissions.

3 Questions to be addressed by Cassini

We look forward to Cassini's arrival at Saturn in 2004 to extend our knowledge of Saturn as a radio source. While not complete, the following are questions and issues which are raised by our current state of understanding of Saturnian radio emissions:

1. Is there a non-axisymmetric component of the planetary magnetic field which is responsible for the strong modulation of Saturn kilometric radiation? If so, quantify the asymmetry. (Obviously, the Cassini MAG instrument will play a fundamental role in this objective.)
2. What is the explanation of the $\sim 1\%$ variation in the radio period recently reported on the basis of Ulysses observations? Can the Galopeau and Lecacheux [2000] (Zarka and Cecconi [2001]) model be verified? Given this, can we extract the rotational component of the periodicity from the combined effects of rotation and the Kelvin–Helmholtz instability on the magnetopause?
3. Does the Kelvin–Helmholtz instability on the magnetopause drive SKR as proposed by Galopeau et al., [1995]? Improve existing knowledge of the source location of SKR and its relationship to the auroral zone and distant magnetosphere and/or magnetopause.
4. What is the fine structure of Saturn kilometric radiation and how does this constrain the generation mechanism?
5. Is there a “Dione effect,” and, if so, what is its mechanism? Is SKR influenced by any other satellites?
6. To what extent can Saturn kilometric radiation be used as a proxy for magnetic activity at Saturn and how well is it correlated with Solar wind input? Is the Saturnian magnetosphere dynamic? If so, how do the dynamics of the Saturnian magnetosphere compare with those of Earth?
7. What is the source of the low-frequency narrowband radio emissions and are these related to the trapped continuum radiation? If these are related to any of the icy

satellites, what is the nature of the magnetosphere–satellite interaction which causes these emissions?

8. Are any of the icy satellites or Titan the source of radio emissions?
9. Is atmospheric lightning the source of SEDs? If so, use them to characterize the occurrence of lightning in Saturn’s atmosphere.
10. What does the source location and low–frequency cutoff of Saturn electrostatic discharges tell us about the spatial and temporal variations of ionospheric plasma densities at Saturn?
11. Are there lightning whistlers due to lightning in Saturn’s atmosphere?
12. Is there lightning on Titan?

A more complete listing of overall Cassini RPWS objectives including plasma waves, thermal plasma, and dust measurements can be found in Gurnett et al. [2001b]. Blanc et al. [2001] address Saturn kilometric radiation objectives in the context of the broader Cassini magnetospheric objectives.

Acknowledgements: We are grateful to M. L. Kaiser for providing Figure 2. The research at the University of Iowa is supported by NASA through Contract 961152 through the Jet Propulsion Laboratory.

References

- Blanc, M., et al., Magnetospheric and plasma science with Cassini–Huygens, *Space Sci. Rev.*, submitted, 2001.
- Burns, J. A., M. R. Showalter, J. N. Cuzzi, and R. H. Durisen, Saturn’s electrostatic discharges: Could lightning be the cause? *Icarus*, **54**, 280–295, 1983.
- Carr, T. D., J. J. Schauble, and C. C. Schauble, Pre–encounter distribution of Saturn’s low frequency radio emission, *Nature*, **292**, 745–747, 1981.
- Connerney, J. E. P., L. Davis, Jr., and D. L. Chenette, Magnetic field models, in *Saturn*, edited by T. Gehrels and M. Matthews, Univ. of Arizona Press, Tucson, 354–377, 1984.
- Connerney, J. E. P., and M. D. Desch, Comment on: ‘Evidence of Saturn’s magnetic field anomaly from Saturnian kilometric radiation high frequency limit’ by P. Galopeau et. al., *J. Geophys. Res.*, **97**, 8713–8717, 1992.
- Davies, M. E., V. K. Abalakin, M. Bursa, J. H. Lieske, B. Morando, D. Morrison, P. K. Seidelmann, A. T. Sinclair, B. Yallop, and Y. S. Tjuffin, Report of the

- IAU/IAG/COSPAR working group on cartographic coordinates and rotational elements of the planets and satellites, *Celest. Mech. Dyn. Astron.*, **63**, 127–148, 1996.
- Desch, M. D., Evidence for Solar wind control of Saturn radio emission, *J. Geophys. Res.*, **87**, 4549–4554, 1982.
- Desch, M. D., Radio emission signature of Saturn immersions in Jupiter’s magnetic tail, *J. Geophys. Res.*, **88**, 6904–6910, 1983.
- Desch, M. D., and M. L. Kaiser, Saturn’s kilometric radiation: Satellite modulation, *Nature*, **292**, 739–741, 1981.
- Desch, M. D., and M. L. Kaiser, Upper limit set for level of lightning activity on Titan, *Nature*, **343**, 442–444, 1990.
- Desch, M. D., and H. O. Rucker, The relationship between Saturn kilometric radiation and the Solar wind, *J. Geophys. Res.*, **88**, 8999–9006, 1983.
- Dougherty, M. K., S. Kellock, D. J. Southwood, A. Balogh, M. Barlow, T. Beek, M. W. Dunlop, R. White, E. J. Smith, L. Wigglesworth, M. Fong, R. Marquedant, B. T. Tsurutani, B. Gerlach, G. Musmann, K.–H. Glassmeier, H. Hartje, M. Rahm, I. Richter, C. T. Russell, D. Huddleston, R. C. Snare, G. Erdos, S. Szalai, F. M. Neubauer, S. W. H. Cowley, and G. L. Siscoe, The Cassini magnetic field investigation, *Space Sci. Rev.*, submitted, 2001.
- Esposito, L. W., et al., The Cassini ultraviolet imaging spectrograph investigation, *Space Sci. Rev.*, in press, 2001.
- Galopeau, P. H. M., P. Zarka, and D. Le Quéau, Theoretical model of Saturn’s kilometric radiation spectrum, *J. Geophys. Res.*, **94**, 8739–8755, 1989.
- Galopeau, P., A. Ortega–Molina, and P. Zarka, Evidence of Saturn’s magnetic field anomaly from Saturnian kilometric radiation high frequency limit, *J. Geophys. Res.*, **96**, 14129–14140, 1991.
- Galopeau, P., and P. Zarka, Reply to comment on “Evidence of Saturn’s magnetic field anomaly from Saturnian kilometric radiation high–frequency limit,” *J. Geophys. Res.*, **97**, 12291–12297, 1992.
- Galopeau, P. H. M., P. Zarka, and D. Le Quéau, Source location of Saturn’s kilometric radiation: The Kelvin–Helmholtz instability hypothesis, *J. Geophys. Res.*, **100**, 26397–26410, 1995.
- Galopeau, P. H. M., and A. Lecacheux, Variations in Saturn’s radio rotation period measured at kilometer wavelengths, *J. Geophys. Res.*, **105**, 13089–13101, 2000.
- Genova, F., B. M. Pedersen, and A. Lecacheux, Dynamic spectra of Saturn kilometric radiation, *J. Geophys. Res.*, **88**, 8985–8991, 1983.
- Gérard, J. C., V. Dols, D. Grodent, J. H. Waite, G. R. Gladstone, and R. Prangé, Simultaneous observations of the Saturnian aurora and polar haze with the HST/FOC, *Geophys. Res. Lett.*, **22**, 2685–2688, 1995.

- Godfrey, D. A., The rotation period of Saturn's polar hexagon, *Science*, **247**, 1206–1208, 1990.
- Gurnett, D. A., The Earth as a radio source: The nonthermal continuum, *J. Geophys. Res.*, **80**, 2751–2763, 1975.
- Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Plasma waves near Saturn: Initial results from Voyager 1, *Science*, **212**, 235–239, 1981a.
- Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Narrowband electromagnetic emissions from Saturn's magnetosphere, *Nature*, **292**, 733–737, 1981b.
- Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Narrowband electromagnetic emissions from Jupiter's magnetosphere, *Nature*, **302**, 385–388, 1983.
- Gurnett, D. A., W. S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, Evidence for a magnetosphere at Ganymede from plasma-wave observations by the Galileo spacecraft, *Nature*, **384**, 535–537, 1996.
- Gurnett, D. A., W. S. Kurth, G. B. Hospodarsky, A. M. Persoon, P. Zarka, A. Lecacheux, S. J. Bolton, M. D. Desch, W. M. Farrell, M. L. Kaiser, H. P. Ladreiter, H. O. Rucker, P. Galopeau, P. Louarn, D. T. Young, W. R. Pryor, and M. K. Dougherty, The Solar wind control of Jovian hectometric radiation and auroral EUV emissions, *Nature*, submitted, 2001a.
- Gurnett, D. A., W. S. Kurth, D. L. Kirchner, G. B. Hospodarsky, T. F. Averkamp, P. Zarka, A. Lecacheux, R. Manning, A. Roux, P. Canu, N. Cornilleau-Wehrlin, P. H. M. Galopeau, A. Meyer, R. Boström, G. Gustafsson, J.-E. Wahlund, L. Aahlen, H. O. Rucker, H. P. Ladreiter, W. Macher, L. J. C. Woolliscroft, H. Alleyne, M. L. Kaiser, M. D. Desch, W. M. Farrell, C. C. Harvey, P. Louarn, P. J. Kellogg, K. Goetz, and A. Pedersen, The Cassini radio and plasma wave science investigation, *Space Sci. Rev.*, in press, 2001b.
- Gurnett, D. A., P. Zarka, R. Manning, W. S. Kurth, G. B. Hospodarsky, T. F. Averkamp, M. L. Kaiser, and W. M. Farrell, Non-detection at Venus of high-frequency radio signals characteristic of terrestrial lightning, *Nature*, **409**, 313–315, 2001c.
- Hunten, D. M., Lightning on Saturn, in *The Atmospheres of Saturn and Titan, Proc. Int. Workshop, Alpbach, Austria, 16–19 September 1985*, **ESA SP-241**, 69–71, 1985.
- Kaiser, M. L., Observations of non-thermal radiation from planets, in *Plasma Waves and Instabilities at Comets and in Magnetospheres*, **Geophysical Monograph 53**, edited by B. T. Tsurutani, and H. Oya, American Geophysical Union, Washington, 221–237, 1989.
- Kaiser, M. L., M. D. Desch, J. W. Warwick, and J. B. Pearce, Voyager detection of nonthermal radio emission from Saturn, *Science*, **209**, 1238–1240, 1980.
- Kaiser, M. L., M. D. Desch, and A. Lecacheux, Saturnian kilometric radiation: Statistical properties and beam geometry, *Nature*, **292**, 731–733, 1981.
- Kaiser, M. L., and M. D. Desch, Saturn kilometric radiation: Source location, *J. Geophys. Res.*, **87**, 4555–4559, 1982.

- Kaiser, M. L., J. E. P. Connerney, and M. D. Desch, Atmospheric storm explanation of Saturnian electrostatic discharges, *Nature*, **303**, 50–53, 1983.
- Kaiser, M. L., M. D. Desch, W. S. Kurth, A. Lecacheux, F. Genova, B. M. Pedersen, and D. R. Evans, Saturn as a radio source, in *Saturn*, edited by T. Gehrels, and M. S. Matthews, University of Arizona Press, Tucson, 378–415, 1984.
- Kaiser, M. L., P. Zarka, W. S. Kurth, G. B. Hospodarsky, and D. A. Gurnett, Cassini and Wind stereoscopic observations of Jovian nonthermal radio emissions: Measurement of beam widths, *J. Geophys. Res.*, **105**, 16053–16062, 2000.
- Kaiser, M. L., W. M. Farrell, M. D. Desch, G. B. Hospodarsky, W. S. Kurth, and D. A. Gurnett, Ulysses and Cassini at Jupiter: Comparison of the quasi-periodic radio bursts, in *Planetary Radio Emissions V* (this issue), edited by H. O. Rucker, M. L. Kaiser, and Y. Leblanc, Austrian Academy of Sciences Press, Vienna, 2001.
- Khan, H., S. W. H. Cowley, E. Kolesnikova, M. Lester, M. J. Brittnacher, T. J. Hughes, W. J. Hughes, W. S. Kurth, D. J. McComas, L. Newitt, C. J. Owen, G. D. Reeves, H. H. Singer, C. W. Smith, D. J. Southwood, and J. F. Watermann, Observations of two complete substorm cycles during the Cassini Earth swing-by: Cassini magnetometer data in a global context, *J. Geophys. Res.*, in press, 2001.
- Krimigis, S. M., Mitchell, D. C. Hamilton, S. Livi, J. Dandouras, S. E. Jaskulek, T. P. Armstrong, A. F. Cheng, G. Gloeckler, K. C. Hsieh, W.-H. Ip, E. P. Keath, E. Kirsch, N. Krupp, L. J. Lanzerotti, B. H. Mauk, R. W. McEntire, E. C. Roelof, B. E. Tossman, B. Wilken, and D. J. Williams, Magnetosphere imaging instrument (MIMI) on the Cassini mission to Saturn/Titan, *Space Sci. Rev.*, in press, 2001.
- Kurth, W. S., D. A. Gurnett, and R. R. Anderson, Escaping nonthermal continuum radiation, *J. Geophys. Res.*, **86**, 5519–5531, 1981a.
- Kurth, W. S., D. A. Gurnett, and F. L. Scarf, The control of Saturn’s kilometric radiation by Dione, *Nature*, **292**, 742–745, 1981b.
- Kurth, W. S., F. L. Scarf, J. D. Sullivan, and D. A. Gurnett, Detection of nonthermal continuum radiation in Saturn’s magnetosphere, *Geophys. Res. Lett.*, **9**, 889–892, 1982.
- Kurth, W. S., D. A. Gurnett, A. Roux, and S. J. Bolton, Ganymede: A new radio source, *Geophys. Res. Lett.*, **24**, 2167–2170, 1997a.
- Kurth, W. S., T. Murata, G. Lu, D. A. Gurnett, and H. Matsumoto, Auroral kilometric radiation and the auroral electrojet index for the January 1997 magnetic cloud event, *Geophys. Res. Lett.*, **25**, 3027–3030, 1998.
- Kurth, W. S., G. B. Hospodarsky, D. A. Gurnett, M. L. Kaiser, J.-E. Wahlund, A. Roux, P. Canu, P. Zarka, and Y. Tokarev, An overview of observations by the Cassini radio and plasma wave investigation at Earth, *J. Geophys. Res.*, in press, 2001a.
- Kurth, W. S., G. B. Hospodarsky, D. A. Gurnett, A. Lecacheux, P. Zarka, M. D. Desch, M. L. Kaiser, and W. M. Farrell, High resolution observations of low-frequency Jovian radio emissions by Cassini, in *Planetary Radio Emissions V* (this issue), edited by

- H. O. Rucker, M. L. Kaiser, and Y. Leblanc, Austrian Academy of Sciences Press, Vienna, 2001b.
- Lecacheux, A., and F. Genova, Source location of Saturn kilometric radio emission, *J. Geophys. Res.*, **88**, 8993–8998, 1983.
- Lecacheux, A., P. Galopeau, and M. Aubier, Re-visiting Saturnian kilometric radiation with Ulysses/URAP, in *Planetary Radio Emissions IV*, edited by H. O. Rucker, S. J. Bauer, and A. Lecacheux, Austrian Academy of Sciences Press, Vienna, 313–325, 1997.
- Lecacheux, A., W. S. Kurth, and R. Manning, Sub-second time scales in Jovian radio emissions as measured by Cassini/RPWS: Comparison with ground-based observations, in *Planetary Radio Emissions V* (this issue), edited by H. O. Rucker, M. L. Kaiser, and Y. Leblanc, Austrian Academy of Sciences Press, Vienna, 2001a.
- Ladreiter, H. P., P. Galopeau, and P. Zarka, The magnetic field anomaly of Saturn, presented at International Symposium on the Magnetospheres of the Outer Planets, Graz, Austria, August 1994a.
- Lammer, H., T. Tokano, G. Fischer, W. Stumptner, G. J. Molina-Cuberos, K. Schwingschuh, and H. O. Rucker, Lightning activity on Titan: can Cassini detect it?, *Planet. Space Sci.*, **49**, 561–574, 2001.
- Lepping, R. P., L. F. Burlaga, and L. W. Klein, Surface waves on Saturn’s magnetopause, *Nature*, **292**, 750–753, 1981b.
- Murata, T., H. Matsumoto, H. Kojima, and T. Iyemori, Correlations of AKR index with Kp and Dst indices, in *Proc. NIPR Symp. Upper Atmos. Physics*, **10**, 64–68, 1997.
- Porco, C., A. Brahic, J. Burns, A. DelGenio, H. Dones, A. Ingersoll, T. Johnson, A. McEwen, C. Murray, G. Neukum, S. Squyres, P. Thomas, J. Veverka, and R. West, The Cassini imaging science investigation, *Space Sci. Rev.*, in preparation, 2001.
- Scarf, F. L., D. A. Gurnett, W. S. Kurth, and R. L. Poynter, Voyager–2 plasma wave observations at Saturn, *Science*, **215**, 587–594, 1982.
- Smith, E. J., L. Davis, Jr., D. E. Jones, P. J. Coleman, Jr., D. S. Colburn, P. Dyal, and C. P. Sonett, Saturn’s magnetosphere and its interaction with the Solar wind, *J. Geophys. Res.*, **85**, 5655–5674, 1980.
- Trauger, J. T., J. T. Clarke, G. E. Ballester, R. W. Evans, C. J. Burrows, D. Crisp, J. S., Gallagher, III, R. E. Griffiths, J. J. Hester, J. G. Hoessel, J. A. Holtzmann, J. E. Krist, J. R. Mould, R. Sahai, P. A. Scowen, K. R. Stapelfeldt, and A. M. Watson, Saturn’s hydrogen aurora: Wide field and planetary camera 2 imaging from the Hubble Space Telescope, *J. Geophys. Res.*, **103**, 20237–20244, 1998.
- Vogl, D. F., H. P. Ladreiter, P. Zarka, H. O. Rucker, W. Macher, W. S. Kurth, D. A. Gurnett, and G. Fischer, First results on the calibration of the Cassini RPWS antenna system, in *Planetary Radio Emissions V* (this issue), edited by H. O. Rucker, M. L. Kaiser, and Y. Leblanc, Austrian Academy of Sciences Press, Vienna, 2001a.

- Voots, G., D. A. Gurnett, and S.-I. Akasofu, Auroral kilometric radiation as an indicator of auroral magnetic disturbances, *J. Geophys. Res.*, **82**, 2259–2266, 1977.
- Warwick, J. W., J. B. Pearce, D. R. Evans, T. D. Carr, J. J. Schauble, J. K. Alexander, M. L. Kaiser, M. D. Desch, B. M. Pedersen, A. Lecacheux, G. Daigne, A. Boischot, and C. H. Barrow, Planetary radio astronomy observations from Voyager 1 near Saturn, *Science*, **215**, 239–243, 1981.
- Warwick, J. W., D. R. Evans, J. H. Romig, J. K. Alexander, M. D. Desch, M. L. Kaiser, M. Aubier, Y. Leblanc, A. Lecacheux, and B. M. Pedersen, Planetary radio astronomy observations from Voyager 2 near Saturn, *Science*, **215**, 582–587, 1982.
- Wu, C. S., and L. C. Lee, A theory of terrestrial kilometric radiation, *Astrophys. J.*, **230**, 621–626, 1979.
- Zarka, P., On detection of radio bursts associated with Jovian and Saturnian lightning, *Astron. Astrophys.*, **146**, L15–L18, 1985a.
- Zarka, P., Directivity of Saturn electrostatic discharges and ionospheric implications, *Icarus*, **61**, 508–520, 1985b.
- Zarka, P., Remote probing of auroral plasmas, in *Planetary Radio Emissions III*, edited by H. O. Rucker, S. J. Bauer, and M. L. Kaiser, Austrian Academy of Sciences Press, Vienna, 351–369, 1992a.
- Zarka, P., Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, **103**, 20159–20194, 1998.
- Zarka, P., Radio emissions from the planets and their moons, *Radio Astronomy at Long Wavelengths in Geophysical Monograph 119*, edited by R. G. Stone, J.-L. Bougeret, K. Weiler, and M. Goldstein, American Geophysical Union, Washington, 167–178, 2000.
- Zarka, P., and B. M. Pedersen, Statistical study of Saturn electrostatic discharges, *J. Geophys. Res.*, **88**, 9007–9018, 1983.
- Zarka, P., and B. Cecconi, Possible explanation for Saturn’s variable radio period, *J. Geophys. Res.*, in preparation, 2001.
- Zarka, P., R. A. Treumann, B. P. Ryabov, and V. B. Ryabov, Magnetically-driven planetary radio emissions and applications to extrasolar planets, *Astrophys. Space Sci.*, **277**, 293–300, 2001b.