Reports

Voyager Detection of Nonthermal Radio Emission from Saturn

Abstract. *The planetary radio astronomy experiment on board the Voyager spacecraft has detected bursts of nonthermal radio noise from Saturn occurring near 200 kilohertz, with a peak flux density comparable to higher frequency Jovian emissions. The radiation is right-hand polarized and is most likely emitted in the extraordinary magnetoionic mode from Saturn's northern hemisphere. Modulation that is consistent with a planetary rotation period of 10 hours 39.9 minutes is apparent in the data.*

Satellite searches for a nonthermal component of Saturn's radio emission have yielded both positive (*1*) and, in a somewhat more limited survey, negative results (*2*). These investigations were conducted from Earth-orbiting and moon-orbiting craft and achieved their greatest sensitivity in the relatively quiet frequency band near 1 MHz, that is, between the spectral peak frequencies of the powerful Jovian and terrestrial radio emitters. This band corresponds very generally to the frequency range predicted for Saturn radio emission on the basis of magnetic Bode's law arguments (*3*) and on the basis of in situ measurements by Pioneer 11 of Saturn's magnetic field strength (*4, 5*).

In the present study, we used the planetary radio astronomy (PRA) instrument (*6*) on board the two Voyager spacecraft to obtain a definitive answer to the question of Saturn's radio emission. By limiting observations to the period of time beginning in January 1980, when the distances of the Voyager satellites to Saturn are less than about 3.7 AU for Voyager 2 (V-2) and 2.8 AU for Voyager 1 (V-1), we minimize contamination from Jupiter radio noise and achieve a gain in sensitivity of at least a factor of 8.5 over that of the near-Earth satellite surveys. Limiting the observations to this time period has also allowed extension of the low-frequency limit of the search to well below 100 kHz. As a result, we confirm that Saturn is a source of nonthermal radio emission, but not in the frequency range near 1 MHz where earlier Earth-orbit identifications were made. Instead, the radio emission takes place below about 300 kHz, that is, in the kilometer-wavelength range. We thus refer to the emission as Saturn kilometer-wave radiation (SKR). In this report we describe the first polarization and spectral measurements of SKR, propose a working figure for a magnetic field rotation rate, and offer plausible explanations for the identification of Saturn made earlier at 1 MHz.

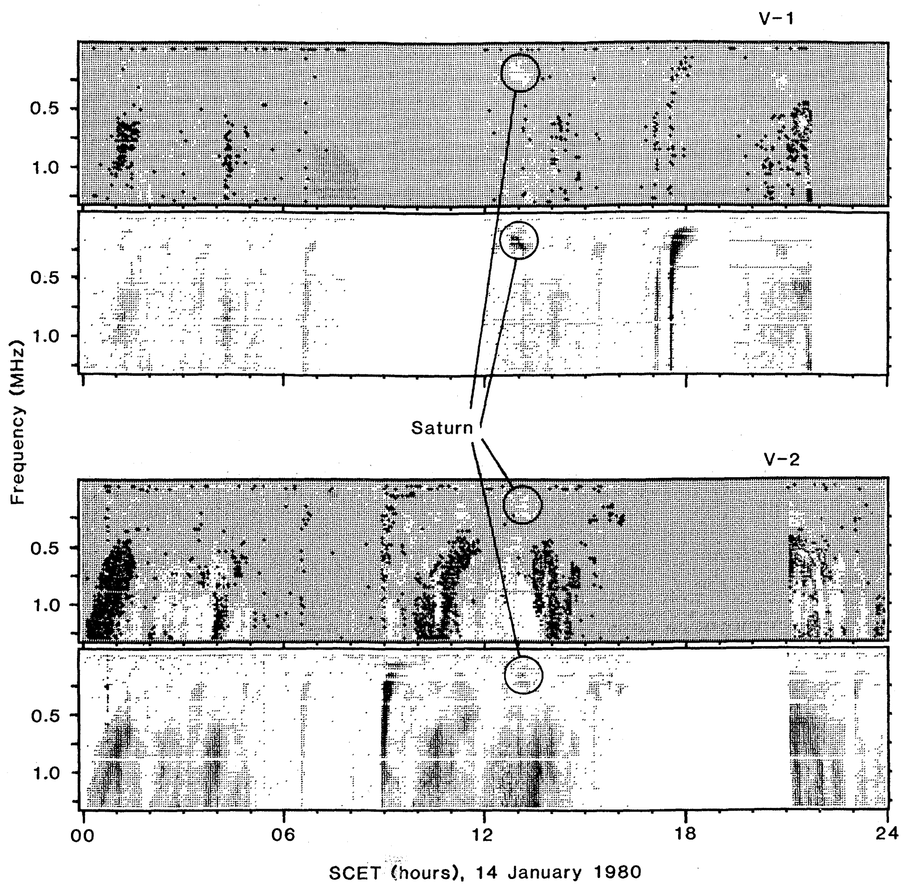


Fig. 1. Simultaneous 24-hour dynamic spectra from V-1 and V-2. The bottom panel of each set indicates total power, with increasing darkness proportional to increasing intensity. The top panel of each set shows the sense of polarization, with white representing right hand and black representing left hand. The indicated Saturn event occurs earlier and is more intense as "seen" by V-1.

Aside from solar type III bursts, which are easily identifiable by virtue of their lack of polarization and by their distinctive dynamic spectral signature, Jupiter radio noise remains the principal source of confusion for the Voyager spacecraft in properly identifying Saturn bursts. However, we have succeeded in discriminating between Jupiter and Saturn on the basis of the following three selection criteria. Where simultaneous V-1 and V-2 coverage exists, only those events were counted for which, first, the signal level on V-1 (which was closer to Saturn) exceeded that on V-2 and, second, the light-time delay between detection by V-1 and V-2 was plausible ($\sim$10 minutes). The third criterion was based on experience gained from the dual spacecraft observations. Specifically, SKR became identifiable in single-spacecraft observations by virtue of its spectral character and polarization sense, which differ from the known Jupiter emission components. Two Jovian radio components have spectral peaks near 100 and 60 kHz (*7, 8*), and the Jovian hectometer-wavelength emission generally exhibits a spectral peak far above 600 kHz. With regard to the polarization sense, the emission that peaks near 60 kHz is always right-hand (RH) polarized as observed from the nightside of Jupiter (*8*) but appears left-hand (LH) polarized in our records owing to its incidence onto the backside of the PRA antenna. As we shall see, this clearly distinguishes it from SKR. Approximately one-third of the events have been identified on the basis of the spectral character and polarization alone. In all, 33 events totaling 24.5 hours of activity have been identified as SKR between 1 January 1980 and

9 February 1980. Our confidence in the correct identification of these events as SKR has grown as the occurrence frequency increases with proximity to Saturn.

In Fig. 1 we show one example of an event detected by both V-1 and V-2, which we have identified as SKR. Each two-panel display (one for V-1 and one for V-2) shows frequency-time spectrograms spanning the same 24-hour period and covering the frequency band from 1 to 1320 kHz. The top panel of each pair illustrates the polarization sense of the radiation with the convention that black corresponds to LH polarized emission and white corresponds to RH polarized emission. The bottom panel of each pair shows wave total power in terms of a gray scale with black corresponding to maximum intensity. The Saturn event, which takes place at 1300 hours SCET (spacecraft event time), is indicated on the spectrograms.

Hectometer-wavelength Jovian emission was still detectable at this time, and it dominates the spectra. A second, weaker SKR event, identified on the basis of its polarization and spectral character alone, is apparent on the V-1 spectrum at 2100 hours SCET.

The SKR event persists for about 0.5 hour, is sporadic at the 3-minute level (our effective resolution limit during this period), and is clearly RH polarized (Fig. 1). The event is stronger and occurs slightly earlier on V-1, as expected. Although not apparent in the plots shown here, examination of the individual RH and LH circular power levels indicates that SKR is strongly RH polarized, with the degree of polarization levels in excess of 60 to 70 percent, on the average. All of the events recorded thus far have been RH polarized.

Figure 2 shows a flux density spectrum of the event in Fig. 1 made at 1302 hours SCET (V-1). The spectral peak is near 200 kHz, and the spectrum falls off to radiometer detection threshold at 59 and 350 kHz. This spectral behavior is fairly typical of the events seen thus far; however, we have also seen SKR extend as high as 500 kHz. Terrestrial kilometric radiation (TKR) exhibits similar spectral characteristics (*9*); because Earth and Saturn possess surface polar magnetic fields of comparable magnitude, one might expect similarities between the two planets with regard to the physical situations giving rise to the radiation.

The total range of frequencies (~60 to ~500 kHz) over which we have observed SKR is entirely within the range to be expected, on the basis of the Pioneer 11 measurements, if emission is at or near

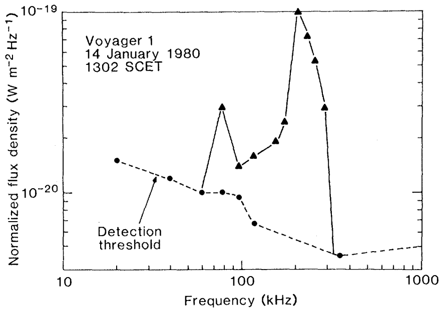


Fig. 2. A normalized flux density spectrum from V-1 at 1302 hours SCET of Fig. 1. The two-peaked structure does not appear to be a permanent feature but rather results in this instance from rapid intensity fluctuations. At the normalized distance of 4.04 AU, Saturn appears as powerful as Jupiter.

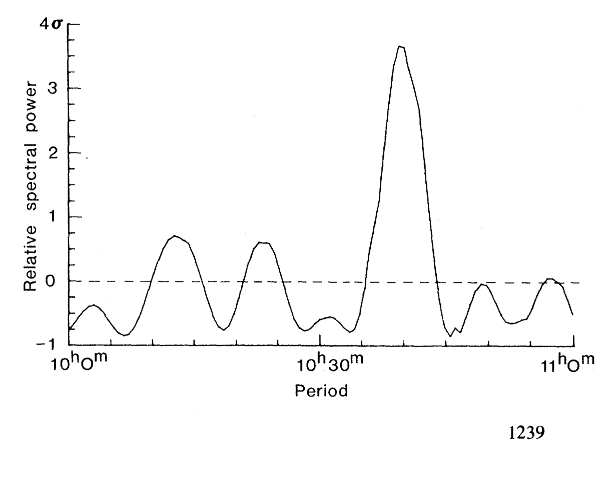
the local electron gyrofrequency. For example, if we restrict attention to Saturn's equatorial region which has a surface field strength of 0.20 G (*4, 5*), we see that the implied source region would extend from 1.04 to 2.10 Saturn radii. This is comfortably above the planet's surface but within what might be regarded as Saturn's inner magnetosphere.

The peak flux density of the event shown in Fig. 2, approximately 10^{-19} W m^{-2} Hz^{-1}, is probably typical of the events we have observed. We have normalized the flux to the standard Earth-Jupiter opposition distance of 4.04 AU in order to facilitate comparisons between the two planets and to show that SKR is as intense at 250 kHz as Jupiter is near its 8-MHz spectral peak (*10*). Our results show that SKR is on the order of 200 times more intense than the average TKR burst and perhaps five times more intense than the peak TKR burst (*9*).

We have thus far observed events with only a single polarization sense, RH. This probably indicates that all of the emissions we observe are issuing from a single magnetic hemisphere on Saturn, either north or south, thus restricting the initial ray vector direction to only one of two situations: the **B**-parallel or **B**-antiparallel geometry, where **B** is the magnetic field. This result does not necessarily imply, however, that only a single hemisphere is active in stimulating radiation. The Voyager-Saturn geometry is such that our observations have been made at a planetocentric latitude near +9°, which corresponds to a constant magnetic latitude of +9° since the magnetic field has been determined by Pioneer 11 investigators to be rotationally axisymmetric or nearly so (*4, 5*). This could effectively exclude from our view LH polarized radiation beamed from the southern hemisphere. Thus, our results are consistent with extaordinary mode emission beamed from the northern hemisphere because such radiation would have its wave vector initially parallel to **B** (Saturn's magnetic moment points in the same sense as Jupiter's) and so would appear RH polarized.

Because of widespread interest in its intrinsic rotation rate, we have attempted to determine Saturn's magnetic rotation period as revealed through the radio occurrence statistics. Similar methods have been used to precisely define System III, the radio rotation rate of Jupiter; however, the data span available for Saturn is greatly limited. With a 40-day base line, we are able to report a provisional rotation period for use in preliminary analyses only. Our result is based on two methods of analysis. First, we stacked all the events in bins covering 360° of rotation, using different rotation periods, until the data were organized preferentially in the smallest number of bins. The best organized data set was identified through the application of a chi-square test to each trial run. Second, we used a method of spectral analysis that is applicable to unequally spaced samples (*11*). Within the uncertainty of the two methods, both have yielded the same result (see Fig. 3). We derive a rotation period of $10^h39.9^m \pm 0.6^m$, where the uncertainty is based on a linear least-squares, goodness-of-fit analysis of the data. This period is within the spread of the measured optical periods for Saturn (*12*),

Fig. 3. The spectral power plotted in terms of normalized standard error between 10 and 11 hours as determined from the method of Deeming (*11*). The major peak is surrounded by side lobes which are caused by heterodyning with a 7.0-day sampling periodicity.



which range from about $10^{h}02^{m}$ at the equator to about $11^{h}03^{m}$ at 57° latitude. By dividing the analysis interval in half and subjecting each half to the above spectral analysis, we can evaluate the secular change in the rotation period. We find that the period is stable to within ± 43 seconds over the analysis interval, or ± 1 second per rotation at the 5 percent confidence limit.

Although it is difficult to judge definitively because of the limited volume of data at hand, it appears that the Saturn events are not organized in rotation phase as tightly as the Jupiter radio events that we have been observing for many years. This was predicted by Acuña and Ness (*4*) on the basis of the Pioneer 11 in situ field measurements, which indicate a rotationally axisymmetric magnetic field for Saturn. It is thus unlike both Jupiter and Earth, which have magnetic dipoles tipped at relatively large angles to their rotation axes. Therefore, any modulation which appears in the SKR is probably due to near-surface anomalies in the field which are undetectable from the Pioneer 11 observations.

In spite of the fact that the ~1-MHz Saturn radio events reported by Brown (*1*) would be more than 20 dB above our present detection threshold, we have failed to record any Saturn emission in the vicinity of 1 MHz. Reexamination of the Interplanetary Monitoring Platform (IMP-6) data used by Brown shows that for much of the period covered by his figures 1 and 2, TKR was clearly evident below 600 kHz. Moreover, the dynamic spectra for this period are strongly reminiscent of Jovian hectometer-wave emission, which was observed often by IMP-6. In a recent study, Fainberg (*13*) has shown that, when two or more radio sources are emitting simultaneously, the IMP-6 direction-finding analysis "points" to the intensity-weighted mean angle between the sources. It is possible that Brown may have observed a signal coincident with the Saturn direction which was formed by a combination of signals from Jupiter and Earth (or perhaps the sun). Another possibility exists if Saturn's radio emission is tightly beamed. During the period of Brown's observations the sub-IMP-6 point on Saturn was at $< -20°$ latitude, as compared with +9° latitude for the Voyager observations reported here. This possibility can be tested after the V-2 encounter in August 1981, when the outbound trajectory reaches large negative latitudes.

Closest approach to Saturn for V-1 is 12 November 1980 and for V-2 is 27 August 1981. During the next year and a half we expect to be able to refine the rotation period. We also plan to search for an LH polarized component and investigate the nature of the rotation modulation of SKR.

Note added in proof: With data analyzed through mid-July 1980 (totaling 202 hours of SKR activity), the best estimate of the Saturnian rotation period is $10^{h}39.4^{m} \pm 0.15^{m}$.

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Human Cutaneous Leishmania in a Mouse Macrophage Line: Propagation and Isolation of Intracellular Parasites

Abstract. *A mouse macrophage line, J774G8, supports continuous and prolific intracellular growth of* Leishmania mexicana amazonensis, *the etiological agent of a South American cutaneous leishmaniasis. The intracellular parasites from these infected cultures can be isolated with high recovery rate and purity by simple Percoll gradient centrifugation.*

Human leishmaniases are parasitic diseases caused by trypanosomatid protozoa of the genus *Leishmania*. Characteristic of all leishmanial infections is the intracellular parasitism of macrophages by amastigotes, the mammalian stage of these parasites responsible for all the symptoms and pathology. The vector stage of leishmania, the promastigote, can be cultured readily in artificial media and has been used frequently for investigation. Unfortunately, very little is known about the intracellular amastigotes because of the difficulties of procuring them in sufficient quantity and purity for investigation. It is now especially urgent to solve this problem in order to deal with the resurgence of the leishmaniases around the world. I report a culture system in which a macrophage cell line is used for continuous propagation of leishmanial amastigotes and a method for their isolation from the cultured material. Until now, these intracellular parasites have not been cultured in large enough numbers for isolation, although similar cell lines were found to support their growth (*1*).

The permanent cell line used for this study was J774G8, originally derived from macrophages of the oil-induced peritoneal exudate of BALB/c mice (*2*). Parasites used were promastigotes of *Leishmania mexicana amazonensis*, which were cultured in a medium previously described (*3*). A macrophage suspension was prepared at a cell density of 10^6 per milliliter in medium RPMI 1640 plus 20 percent heat-inactivated fetal bovine serum (HIFBS) and Hepes buffer. This suspension was added to parasites pelleted by centrifugation at a parasite to macrophage ratio of 10 to 1 and then mixed thoroughly. The mixture was placed in tightly capped tissue culture flasks and incubated at 35°C. During the first 3 days, promastigotes gained entry into the macrophages, transformed into amastigotes, and induced the formation of huge vacuoles characteristic of this leishmania species (Fig. 1A). On day 3 and every 3 days thereafter, cells were removed from the culture flask by vigorous rinsing with a Pasteur pipette, the medium was renewed, and the intracellular parasites were counted. For change of medium, cells were centrifuged at 200*g* for 3 minutes, suspended in fresh medium, and returned to the original flask. For counting the intracellular parasites, a thin wet mount was made by covering 10 μl of the culture fluid with a 22-mm² cover slip on a slide. The percentage of infected cells and the average numbers of amastigotes per cell were determined by examining at least 100 macrophages by phase-contrast microscopy with an oil immersion lens. The total number of macrophages was determined from the volume of the culture and mac-

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