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LOW FREQUENCY RADIO EMISSIONS FROM JUPITER: JOVIAN KILOMETRIC RADIATION

W. S. Kurth[1], D. D. Barbosa[1], F. L. Scarf[2], D. A. Gurnett[1], and R. L. Poynter[3]

[1] Department of Physics and Astronomy, The University of Iowa, Iowa City, IA 52242
[2] Space Sciences Department, TRW Defense and Space Systems Group, Redondo Beach, CA 90278
[3] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91103

Abstract. A new component of the Jovian radio spectrum has been observed by the plasma wave instruments on Voyagers 1 and 2 at frequencies ranging from about 10 to 56 kHz or higher. This Jovian kilometric radiation is characterized by storms of emissions lasting typically 45 minutes at 56.2 kHz, however some events persist for as long as four hours. The storms usually exhibit impulsive bursts with time scales of a few seconds to several minutes, although some events show smoothly varying intensities as a function of time. High resolution frequency-time spectrograms reveal a continuum-like background with more intense, narrowband features superimposed. The narrowband, or discrete, features tend to decrease in frequency with increasing time, falling ~ 1 kHz in 5 to 60 seconds. The maximum power emitted assuming an isotropic radiator near Jupiter and a bandwidth for the most intense bursts of ~ 10 kHz is about 10^9 watts. The Jovian kilometric radiation is most likely observed within ±45° of 200° System III longitude, λ_{III}, although there is a secondary maximum near $\lambda_{III} = 25°$.

Introduction

Since the discovery in 1955 that Jupiter is a source of radio emissions at decametric wavelengths [*Burke and Franklin*, 1955], the known Jovian radio spectrum has grown in scope and complexity. The planet is now commonly known to be emitting at decimetric wavelengths (see review by *Berge and Gulkis* [1976]) as well as in the decametric and hectometric regimes (see reviews by *Carr and Gulkis* [1969] and *Carr and Desch* [1976]). With the approach of Voyager 1 to Jupiter in late 1978 and early 1979 comes the discovery of still another component of the Jovian radio spectrum at kilometric wavelengths [*Scarf et al.*, 1979; *Warwick et al.*, 1979]. This paper reports the initial observations of this new Jovian radio emission by the plasma wave instruments on board Voyagers 1 and 2.

The first clear detection of the new Jovian emission was made in early October, 1978 when Voyager 1 was still ~ 1 AU from Jupiter. As the spacecraft approached the planet, observations of the radio waves became increasingly more common, primarily in the 56.2-kHz channel of the plasma wave receiver. The purpose of this paper is to describe the spectral and temporal character of the radiation, as well as periodicities encountered in the observation of the emission during the inbound leg of the Voyager 1 encounter. The Voyager plasma wave instrument is described by *Scarf and Gurnett* [1977].

Observations Of Jovian Kilometric Radiation

A representative example of a Jovian kilometric radiation event is shown in Figure 1 which is a plot of electric field spectral density as a function of time for the seven highest frequency channels of the plasma wave instrument. For each channel, the spectral density averaged over 24-second intervals is represented by a solid black area with height proportional to the logarithm of the spectral density. The peak intensities measured during the same 24-second intervals are plotted as a line above the averages. The observed peak in this event is at 56.2 kHz, although the emission could extend to higher frequencies above the frequency range of the instrument. *Warwick et al.* [1979] report that the emission sometimes extends as high as several hundred kHz. The intense burst at 56.2 kHz between ~ 1220 and ~ 1310 UT (all times mentioned herein are spacecraft event times, i.e., corrected for one way light time from the spacecraft) is characterized by numerous rapid fluctuations in intensity with some fluctuations of nearly 10 db occurring on a time scale of a few seconds. This impulsive nature is also seen in the 31.1- and 17.8-kHz channels. The event exhibits very smooth temporal variations in time after about 1310 UT in the 56.2-kHz channel. Since a Type III solar burst was detected nearly simultaneously by the planetary radio astronomy instrument [*M. L. Kaiser*, personal communication, 1979], it is possible this smooth portion of the event is a Type III burst, however, the sporadic nature and large amplitude of the event prior to 1310 UT rule out the solar burst interpretation for the earlier portion of the event.

The event in Figure 1 also provides proof that these are not locally generated waves, but freely propagating electromagnetic waves. The 3.11-kHz channel shows a series of very impulsive bursts which are well confined in frequency. These are electron plasma oscillations which are local oscillations at the solar wind plasma frequency. The low frequency cutoff of the radio burst is near 10 kHz, hence, the solar wind plasma in the vicinity of the spacecraft cannot interact with the radio waves and the low frequency cutoff of the emission is not a local effect. Since 10 kHz is consistent with plasma frequencies and densities measured in the Jovian magnetosheath [*Scarf et al.*, 1979; *Bridge et al.*, 1979] it is reasonable to assume that the magnetosheath is responsible for the lower frequency cutoff of the Jovian kilometric radiation.

While it was not possible to identify the upper frequency limit of the event in Figure 1, many examples exist which exhibit a peak in intensity at frequencies lower than 56.2 kHz. For example, the event in Figure 2 clearly peaks near 31.1 kHz and apparently has a bandwidth comparable to or narrower than the 4.2 kHz bandwidth of the 31.1 kHz filter.

Another feature of Jovian kilometric radiation which is demonstrated by the event of Figure 2 is a tendency for bursts to drift to lower frequencies with increasing time. Notice that there is activity in the 56.2-kHz channel at 0855 UT in Figure 2, but there is no activity at 31.1 kHz until about 0905 UT and the event commences still later at 17.8 kHz. A similar effect is seen in Figure 1 where the peak intensity for the event occurs later in time for each successive channel going toward lower frequencies. Figure 3 is an example of a fairly complex event consisting of a number of individual bursts occurring over a time span of nearly three hours. Each of the bursts appears to peak at increasingly later times as the frequency decreases. While not all events show this negative drift, it is observed in a large number of cases; very few bursts appear to drift to higher frequencies.

To obtain a more detailed spectrum of Jovian kilometric radiation, we have searched for events which extend to frequencies below 12 kHz at a time when 115.2 kb/s waveform data are available. This special mode of the plasma wave receiver provides high resolution frequency information below 12 kHz. One such case was found while Voyager 1 was within the Jovian magnetosphere. The spectrum shown in Figure 4 is a six-second average taken on March 8, 1979, at a radial distance of 55 R_J. Here, the strongest feature is Jovian nonthermal continuum radiation, analogous to terrestrial continuum radiation [*Gurnett*, 1975] which has a lower frequency cutoff at the local electron plasma frequency, in this case about 1 kHz. The electron gyrofrequency is well below 1 kHz at this time [*N. F. Ness*, personal communication, 1979]. Hence, waves detected well above 1 kHz

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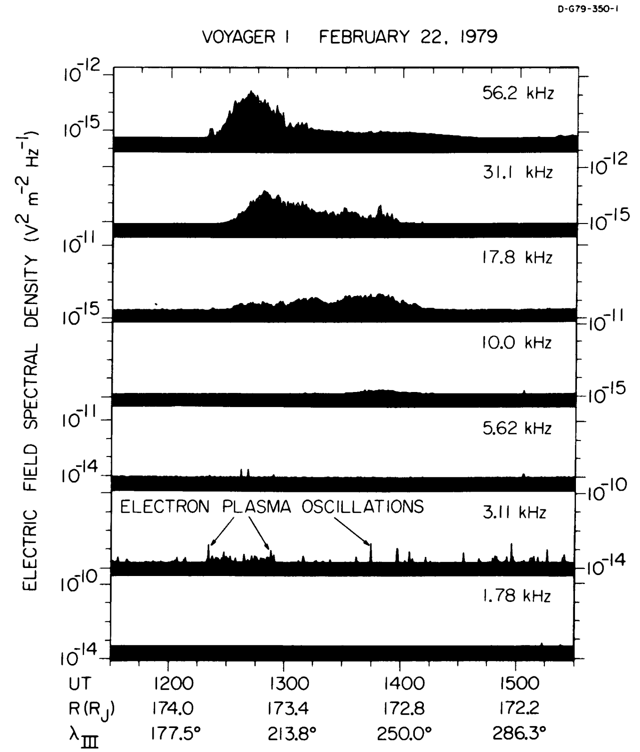

Fig. 1. Spectral density as a function of time for the upper seven channels of the Voyager 1 plasma wave instrument during a Jovian kilometric radiation event. Notice the sporadic nature of the burst during much of the event.

must be freely propagating electromagnetic waves and not local phenomena. The abrupt decrease in the continuum radiation spectrum at about 3 kHz indicates the transition from the lower frequency, trapped component to the freely escaping continuum radiation. The feature above 5 kHz in Figure 4 is the kilometric radio emission of interest here.

The kilometric radiation spectrum shown in Figure 4 shows wave amplitudes well above the untrapped continuum spectrum with intense, narrowband features at about 9 and 12 kHz. The bandwidth of these intense features is about 2 kHz or less. (The two minima labeled notch filters refer to filters in the receiver designed to remove interference from the spacecraft power supply, which operates at 2.4 kHz, and its third harmonic.) The discrete feature at 9 kHz is similar to the bursts seen in Figure 3 and, hence, may exhibit complex temporal behavior. Figure 5 is a high resolution, frequency-time spectrogram provided to show the detailed temporal variations of the spectrum displayed in Figure 4. Figure 5 shows the intensity of frequency components from 0 to 12 kHz as a function of time for a 48-second interval. For reference, the spectrum in Figure 4 was averaged between 1000:20 and 1000:26 UT. The dark band of emission between 1 and 3.5 kHz is the trapped continuum radiation and the kilometric radiation is evident above about 5 kHz. The intense feature at 9 kHz in Figure 4 is clearly evident in Figure 5. Additional structure exists near the 12 kHz upper cutoff of the receiver. The two vertical white stripes near 1000:03 and 1000:26 UT are times when the low energy charged particle instrument's stepper motor interfered with the plasma wave receiver at about 300 Hz and caused the automatic gain control (AGC) receiver to be set to a very low gain. Again, the white bands at 2.4 and 7.2 kHz are the effect of the receiver's notch filters.

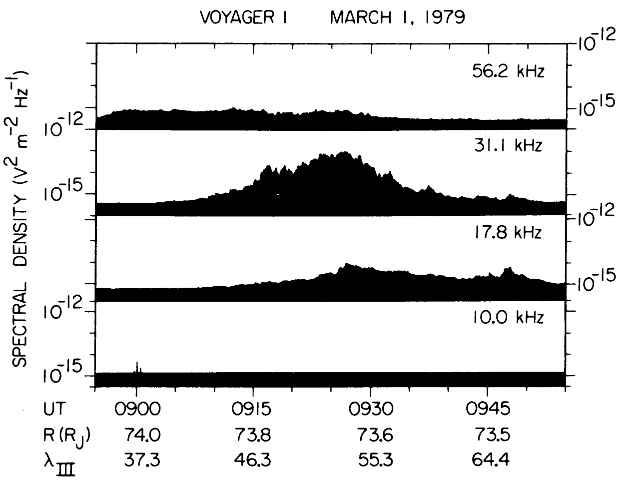

Fig. 2. An example of a kilometric radio burst which appears to peak at 31.1 kHz. There is a relatively low-level background component extending from 17.8 to 56.2 kHz with a relatively narrowband feature at 31.1 kHz.

It appears from Figure 5 that the kilometric radiation consists of two components of different character. First, there appears to be a relatively homogeneous emission at low intensities from 5 kHz to above 12 kHz. (Using the step-frequency receiver portion of the instrument we know this event extends to at least 56.2 kHz.) Second, there are discrete, relatively intense emissions with narrow bandwidths which are superimposed on the background. Most interesting is the apparent drift of the discrete features to lower frequency as a function of time. The drift rates are variable from one emission to another, but are roughly 1 kHz per 5 seconds. A review of the first three figures reveals basically the same characteristics, that is, a relatively uniform, low level background emission and discrete features which drift to lower frequencies with time. Figure 3, for example, displays drift rates ranging from about 1 kHz per 5 seconds to nearly 1 kHz per minute.

The gross temporal character of the Jovian kilometric storms are not easily described because of striking differences from event to event. A survey of Figures 1-3 reveals the range of variations in event morphology present in the Voyager 1 data. It is clear, however, that some unifying statements can be made. The duration of the storms at 56.2 kHz is typically 45 minutes and ranges from a few minutes to four or more hours. Intense bursts occurring within the storms, however, usually last no longer than about 30 minutes and often are much shorter.

The intensity of the bursts is highly variable from one event to another and, of course, those events detected closer to Jupiter are in general stronger than the early events detected at large radial distances. We can estimate the peak total power emitted during an event by assuming isotropic radiation from a source

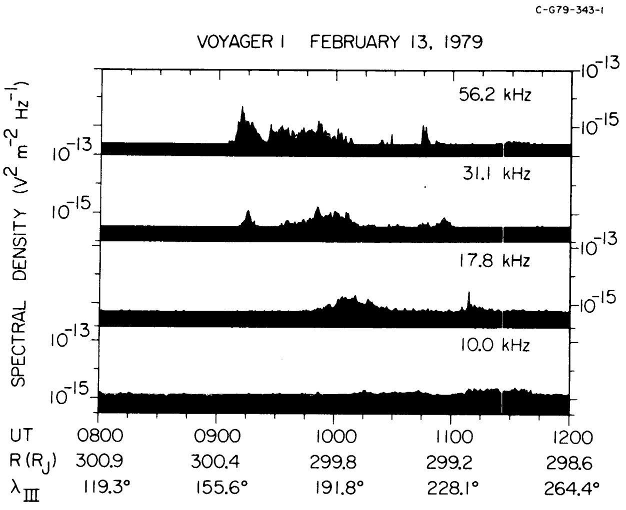

Fig. 3. A storm of Jovian radio kilometric bursts which drift to lower frequencies with time at varying rates.

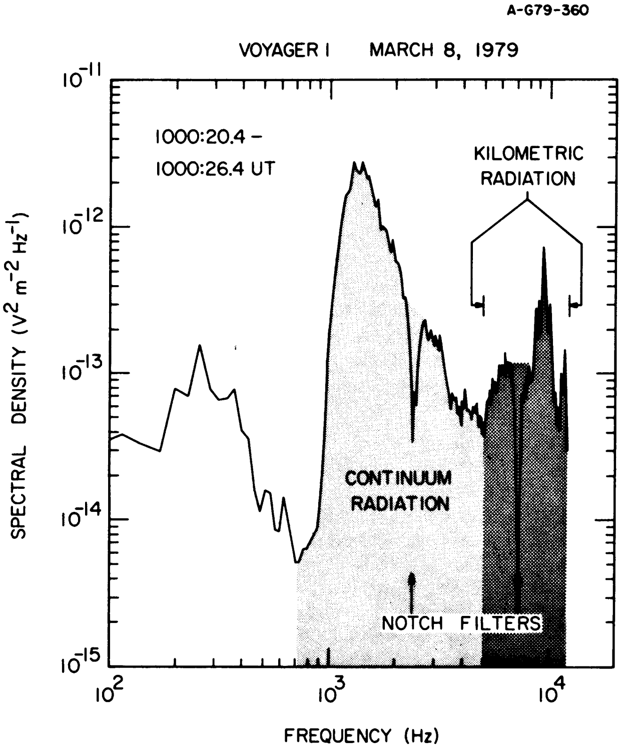

Fig. 4. A high-resolution spectrogram of kilometric radiation detected within the Jovian magnetosphere. The kilometric spectrum is accentuated by intense, narrowband features.

near Jupiter. For the most intense events detected, this estimate is 10^5 W Hz^{-1}. It is most likely the feature emitting so intensely is one of the discrete features observed above which typically have bandwidths of $\lesssim$ 10 kHz at 56.2 kHz. Hence, the total power is about 10^9 watts. To put this in proper perspective, the power emitted in the form of decametric radiation is approximately 10^8 W [*Warwick*, 1967]. We have assumed isotropy for simplicity even though there appears to be a region near the magnetic equator which is poorly illuminated. Until the Solar Polar spacecraft approach Jupiter at much higher latitudes, however, it will be difficult to determine whether or not the kilometric radiation illuminates broad solid angles over the poles, as is the case with auroral kilometric radiation at the earth.

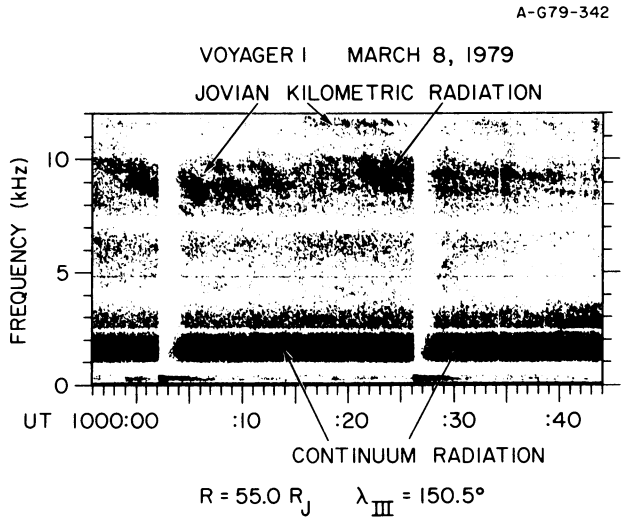

Fig. 5. A high-resolution, frequency-time spectrogram showing the 48-second interval centered on the spectrum shown in Figure 4. Notice the kilometric radiation appears as diffuse, low-level waves above 5 kHz with relatively intense, narrowband features superimposed. The discrete features appear to drift to lower frequencies with time.

Using Voyager 1 data from October 1, 1978, through March 1, 1979, we have performed an initial synoptic study of the occurrence of Jovian kilometric radiation as a function of System III (1965) longitude, λ_{III}, and the departure of Io from superior conjunction as seen from Voyager, φ_{Io}. (Superior conjunction occurs when the System III longitudes for Voyager and Io differ by 180°.) The results of this synoptic study are shown in Figure 6, which represents all of the events above the receiver threshold (close to 10^{-16} $V^2m^{-2}Hz^{-1}$) during the inbound leg of the Voyager 1 encounter. The vertical bars are proportional to the logarithm of the amplitude of the 56.2-kHz channel response above receiver noise level with the bottom of each bar at the coordinates of λ_{III} and φ_{Io} of Voyager and Io when the measurement was made. Each bar represents a 96-second average of the signal strength. No correction has been made for a R^{-2} dependence of the signal strength, hence, care must be exercised in the interpretation of the relative amplitudes of events. At the same time, however, it is possible to quickly survey the morphology of events with this display.

The main conclusion from this synoptic study is that the kilometric radiation is most likely observed when Voyager is near $\lambda_{\text{III}} = 200°$. Roughly 50% of the events occur within ±45° of this longitude, which is the approximate longitude of the north magnetic pole. There also appears to be a cluster of events in the range $\lambda_{\text{III}} = 25 \pm \sim 50°$, although this occurrence peak is secondary to the one near 200°. There may also be a very weak Io effect on the source near $\lambda_{\text{III}} = 25°$. A paucity of events can be seen in the $\lambda_{\text{III}} \approx 25°$ source in the range $135 \lesssim \varphi_{\text{Io}} \lesssim 225°$, that is, when Io is between Jupiter and the spacecraft, however, a broader statistical base is required to verify this effect.

Discussion

The two main questions which must be answered in regard to the Jovian kilometric radiation are (1) where is the emission region, and (2) what is the emission mechanism. While it is somewhat premature to expect to answer these questions at this point, it is useful to reflect upon these questions in light of the observations presented above.

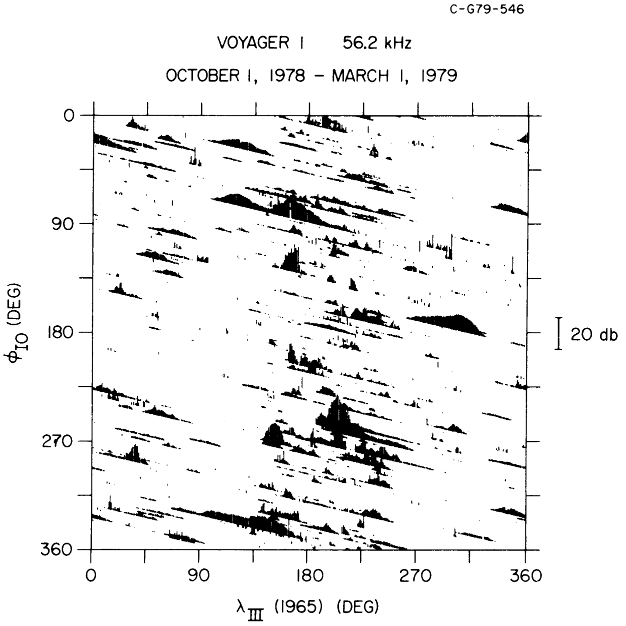

Fig. 6. The result of a synoptic study of the occurrence of Jovian kilometric radiation as a function of System III longitude and the departure of Io from superior conjunction ($\varphi_{\text{Io}} = 0°$). Approximately half of the events occur within ±45° of $\lambda_{\text{III}} = 200°$ with a secondary maximum in occurrence frequency near $\lambda_{\text{III}} = 25°$.

There are two reasonable possibilities for the location of the kilometric radio source region. The first candidate is a region above the poles of Jupiter. This choice is directly motivated by the peak in occurrence frequency near $\lambda_{III} = 200°$. This is approximately the direction of the magnetic dipole in the northern hemisphere; hence, the source is most visible when the pole is tilted toward the spacecraft. There is also a relative maximum in occurrence frequency when the southern pole is tilted toward the spacecraft and the relative dominance of the northern source could be due to the fact that Voyager is north of the equator on the inbound leg albeit only by 3°.

The alternate possibility is that the source is associated with the Io plasma torus [*Broadfoot et al.*, 1979; *Warwick et al.*, 1979]. This hypothesis has the desirable feature that relatively intense electrostatic waves near the upper hybrid resonance frequency have been detected in the region of the torus over about the same frequency range as reported for Jovian kilometric radiation [*Scarf et al.*, 1979; *Warwick et al.*, 1979]. It is possible that these electrostatic waves may couple to electromagnetic waves and, thus, be the source of the kilometric radiation. It is difficult to see, however, how the longitudinal dependence of the kilometric radiation can be explained if the Io torus is the source, without resorting to complex beaming models.

The source mechanism is a question of even greater speculation than the source region, partly because a good knowledge of the source region is necessary to characterize the plasma distributions involved in the generation mechanism. One observation in particular may provide some insight on this question. The frequency-time spectrogram of Figure 5 shows continuum-like characteristics as do other high resolution spectrograms examined to date. We should consider, then, that at least the continuum-like component of the kilometric radiation may be generated in the same manner as Jovian continuum radiation, but at a higher frequency. Of course, the generation mechanism for Jovian continuum radiation remains to be explained, also, but terrestrial continuum radiation is thought to be either synchrotron emission [*Frankel*, 1973] or generated from intense electrostatic bands near the upper hybrid resonance frequency [*Gurnett*, 1975; *Kurth et al.*, 1979].

It is interesting to speculate, also, on the source of the discrete kilometric emissions. The discrete emissions shown in Figure 5 are similar in form to high resolution spectrograms of auroral kilometric radiation from the earth [*Gurnett et al.*, 1979], except that the terrestrial auroral emission consists of predominantly rising features with some falling features. It is speculated that this frequency drift is related to the velocity of an excitation process with a component parallel to either a density gradient or magnetic field gradient. For example, one could envision excitation of Jovian kilometric radiation taking place at successively larger radial distances as a function of time such that the local plasma has either a lower density and/or gyrofrequency at each point of excitation.

Conclusion

The plasma wave instrument on Voyager 1 has detected a new component to the Jovian radio spectrum at kilometric wavelengths. The emission is seen from as low as about 10 kHz to the 56.2 kHz upper frequency limit of the instrument with peak total power estimated at about 10^9 watts. High-resolution frequency-time spectrograms show a relatively featureless, low-level background emission with more intense discrete emissions which tend to drift to lower frequencies with time. The kilometric radiation is observed most often near $\lambda_{III} = 200°$ with a secondary occurrence frequency peak near 25°. The 25° source may exhibit a weak Io control.

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