JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. A6, PAGES 6917–6924, JUNE 1, 1989

# Jovian Type III Radio Bursts

W. S. KURTH AND D. A. GURNETT

*Department of Physics and Astronomy, University of Iowa, Iowa City*

F. L. SCARF[1]

*TRW Space and Technology Group, Redondo Beach, California*

Radio bursts have been observed in the Voyager plasma wave data from Jupiter that bear a striking resemblance to solar type III radio bursts. The emissions lie in the frequency range near 10 kHz, have durations of a minute or so, and occur in a set of periodically spaced bursts. The spacing between primary bursts is typically 15 min, but the bursts may have additional components which recur on time scales of about 3 min. The similarity with solar type III radio bursts suggests a source mechanism involving the movement of energetic electrons through a density gradient in the plasma surrounding Jupiter. The periodicity of bursts suggests Io may be involved in the generation of waves, since the timing is similar to the Alfvén wave travel time from one hemisphere to the other through the Io torus.

## INTRODUCTION

Comparisons between Jupiter and stars have often been made, primarily because of the large mass of Jupiter and the fact that it possesses many stellar attributes. Herein we describe another newly discovered attribute, namely radio emissions that are strikingly similar to solar type III radio bursts.

The radio spectrum of Jupiter is the richest of the planets and has been studied the longest, dating back to the discovery of Jovian radio emissions by *Burke and Franklin* [1955]. Pre-Voyager studies of the low-frequency part of the Jovian spectrum, lying below about 10 MHz, are rare [*McCulloch and Ellis*, 1966; *Zabriskie*, 1970]. In the regime below 100 kHz the heretofore identified components include narrow-band kilometric radiation [*Kaiser and Desch*, 1980], the lower-frequency portion of broadband kilometric radiation [*Warwick et al.*, 1979], continuum radiation [*Scarf et al.*, 1979], and narrow-band electromagnetic radiation [*Gurnett et al.*, 1983]. Now we add an additional component in the frequency range of about 10 kHz.

The new emissions reported here consist of bursts with durations of the order of a minute or so, bandwidths on the order of a few kilohertz at center frequencies near 10 kHz, and frequency-time spectra remarkably similar to solar type III radio bursts. The Jovian emissions occur as a series of bursts separated by time intervals of about 15 min. The series typically last for 1 or 2 hours. Such characteristics are sufficient to differentiate between these and previously identified Jovian radio emissions.

The new radio bursts which we describe below were identified in the Voyager plasma wave waveform receiver data. These data provide temporal and spectral resolution sufficient to differentiate the new bursts from simple temporal variations in the other radio emissions present in the same frequency range. The Voyager plasma wave receiver is described in detail by *Scarf and Gurnett* [1977].

## OBSERVATIONS

The basic features of the new Jovian radio bursts can be seen in Figure 1. The format of Figure 1 is a frequency-time spectrogram with the intensity plotted as a function of time (abscissa) and frequency (ordinate). Black indicates the strongest wave intensities, and white the weakest. The time scale in Figure 1 is 1 hour and 10 min and represents the temporal compression of about seventy-five 48-s frames of waveform data. The bars across the top of the display represent periods when data were available. For the dozen or so 48-s intervals near the center of the plot where there is no waveform data, we have interpolated across the gaps.

Figure 1 shows three events occurring just after 1100 spacecraft event time (SCET) on February 28, 1979, with evidence for additional emissions before and after the three at much lower amplitudes. The bursts start at about the 12-kHz upper frequency limit of the display and extend down to just below 9 kHz. Each of the bursts appears to start at the highest frequency and drift rapidly to lower frequencies; the duration at 12 kHz is about 1 min, while it is closer to 3 min near the lower-frequency extent of the bursts. These data were obtained when Voyager 1 was in the upstream solar wind and approaching Jupiter at a distance of 87.5 $R_J$. At this time the electron plasma frequency was near 4 kHz [*Bridge et al.*, 1979], and the electron cyclotron frequency was about 30 Hz [*Ness et al.*, 1979]. Since the waves of interest are at much higher frequencies, it is certain that they are electromagnetic "radio" waves and not local plasma waves.

The first prominent event in Figure 1 begins at about 1106 SCET. The second and third events begin at about 1123 and 1138 SCET, respectively. Hence on the basis of these start times the events are spaced at intervals of about 16 min. Each event actually comprises two or more bursts. The first event is shown in greater temporal detail in Plate 1 to allow one to see the decomposition of the event into as many as four bursts. In Plate 1, red indicates the most intense waves, and blue the weakest. Notice that the first event occurs during a time when continuous data are available, hence no interpolation was necessary.

Plate 1 shows the frequency-time character of the individual bursts in detail. It also shows the relative timing of the

---

[1] Deceased July 17, 1988.

Paper number 89JA00166.
0148-0227/89/89JA-00166$02.00

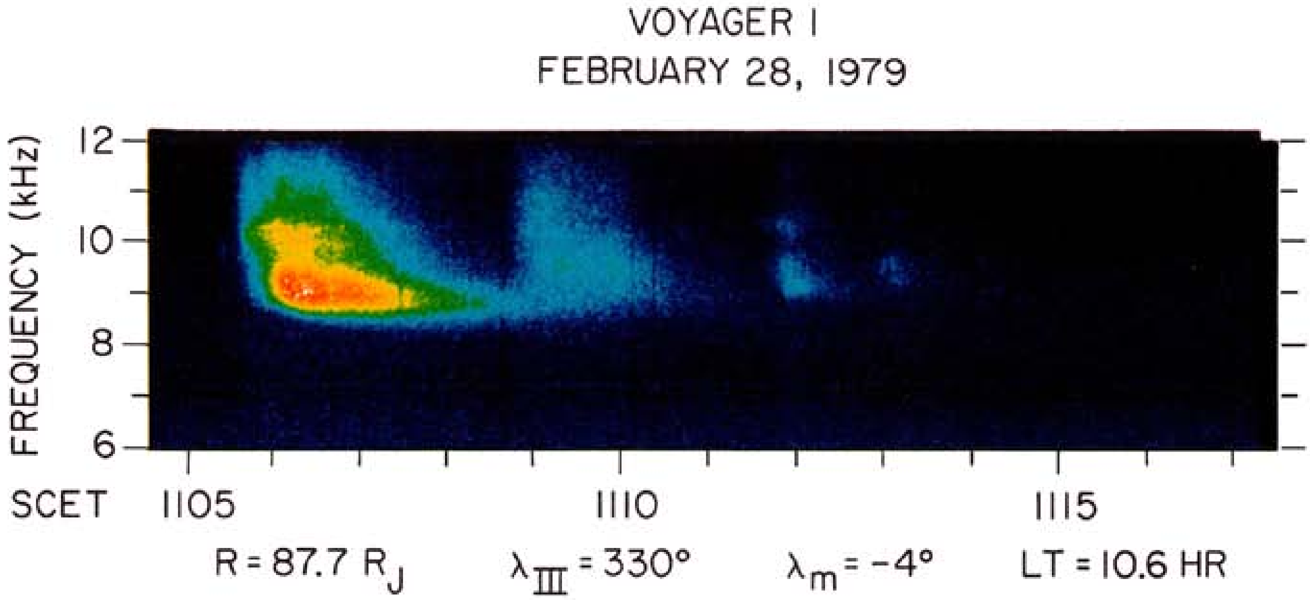

Plate. 1. An expanded view of the first set of emissions from Figure 1 showing the remarkable similarity in the appearance of the radio bursts to solar type III bursts.

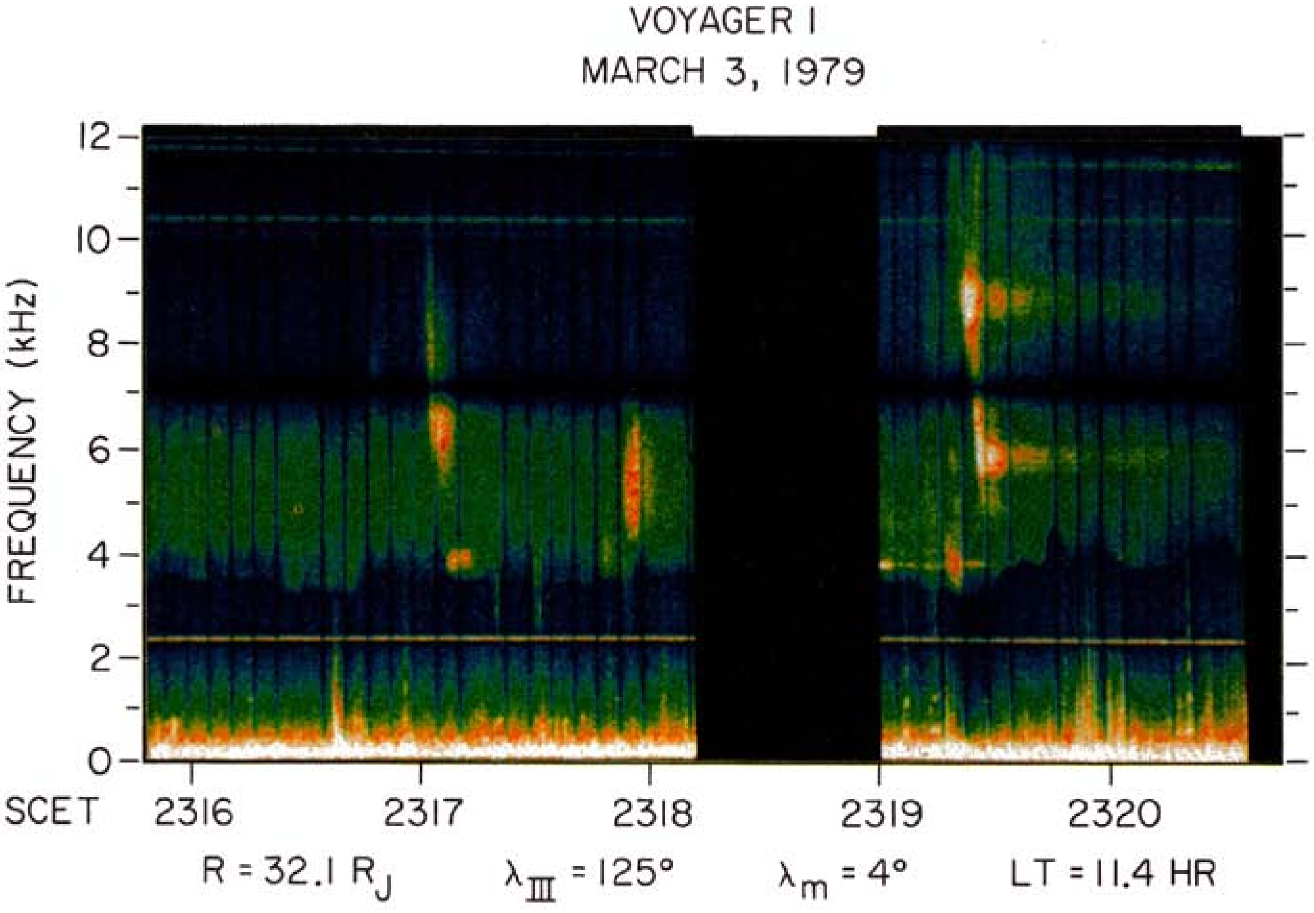

Plate 2. Additional radio bursts with frequency-time characteristics similar to the bursts in Plate 1. The second event is evidently related to the intensifications in the continuum radiation in some way.

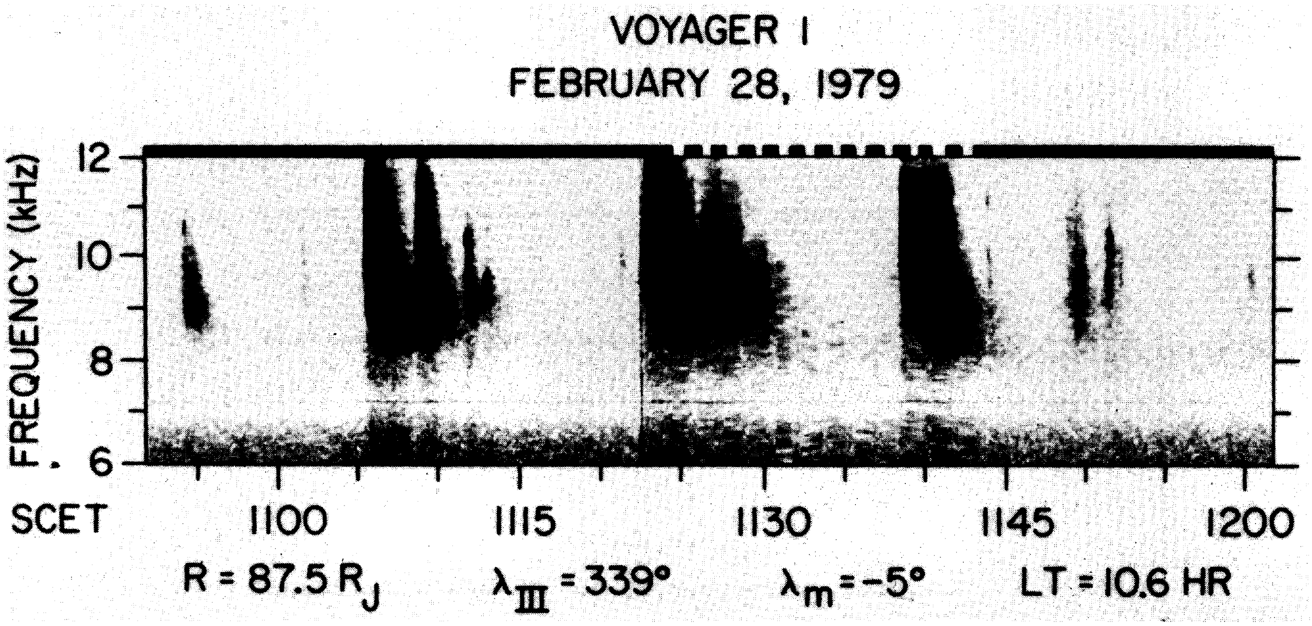

Fig. 1. A frequency-time spectrogram showing a series of radio emissions spaced at regular intervals in time with multiple components.

bursts within the event. The second burst begins about 3 min after the first, the third about 3 min after the second, and what may be a fourth burst begins about 1 min after the beginning of the third. Generally speaking, the intensity and frequency extent of the bursts decrease from one to the next. The trend of decreasing bandwidth may simply be a result of the lower intensity of the later emissions and the limited sensitivity of the receiver.

We should point out that the events described herein all occur in a frequency range above the local electron plasma frequency and cyclotron frequencies, hence the emissions are radio waves and not local plasma waves. While Voyager does not have a magnetic sensor to confirm an electromagnetic character to these emissions, electrostatic plasma instabilities cannot propagate at such high frequencies.

Using the first burst of the event of Plate 1 as a prototypical burst, we point out the similarities of these Jovian emissions with solar type III radio bursts. The solar emission typically commences at a frequency of a few hundred megahertz and drifts to 100 kHz or below at a drift rate of about 20 MHz/s. The duration of the solar bursts ranges from less than 1 min at the highest frequencies to of the order of 1 hour at 100 kHz. A comparison of the main burst in Plate 1, then, with a solar type III radio burst would be qualitatively very good. That is, if one adjusts for the different time and frequency scales, the appearance of the Jovian and solar bursts is quite similar. For this reason we have labeled the new Jovian emissions as Jovian type III radio bursts. The differences in spectral and temporal extent are ultimately tied to differences in the plasma densities and the extent of the emitting regions in the two sources, as will be discussed in the next section. A comparison of some of the solar type III and Jovian burst characteristics is presented in Table 1.

With the similarities noted above, we should be careful to point out that it is clear that the bursts in Figure 1 are not of solar origin. The arguments are that the Voyager plasma wave receiver detected very few solar bursts after passing beyond 2–3 AU, and the few that have been observed seldom extend below the 31.1-kHz channel of the spectrum analyzer. Further, as mentioned above, the durations of solar type III bursts at 100 kHz (and below) are typically an hour and have not been observed to last for only a couple of minutes at such low frequencies. Finally, as will be shown below, there is no evidence that the Jovian bursts extend much above 20 kHz.

The wideband waveform data like those shown in Figure 1 and Plate 1 require a very high data rate to be transmitted from Voyager (115,200 bits/s). Hence these data compete with the Voyager imaging system for telemetry, and the coverage is by no means comprehensive. Accordingly, it is not possible to do a meaningful search for other events using the wideband data. Complete coverage is afforded by the lower data rate and lower resolution spectrum analyzer data, and we can use that to search for other events.

In order to characterize the appearance of the Jovian bursts in the spectrum analyzer data, we have plotted data from the 5.62-, 10-, 17.8-, and 31.1-kHz channels of the plasma wave spectrum analyzer for a period of time similar to that of Figure 1 in Figure 2. Plotted as solid black areas is the average power flux as a function of time in each of the

TABLE 1. Comparison of Characteristics of Solar and Jovian Type III Bursts

| Emission | $f_{\max}$, kHz | $f_{\min}$, kHz | $\tau\,(f_{\min})$, s | Periodicities | Dynamic Spectrum |
|---|---|---|---|---|---|
| Solar | $5 \times 10^5$ | 30 | 4000 | no | drifts to lower $f$ at 20 MHz/s |
| Jovian | 20 | 5 | 200 | yes | drifts to lower $f$ at 1 kHz/s |

A summary of spectral and temporal characteristics of solar and Jovian type III radio bursts. The parameter $\tau(f_{\min})$ is the duration of the emission at its lowest frequency.

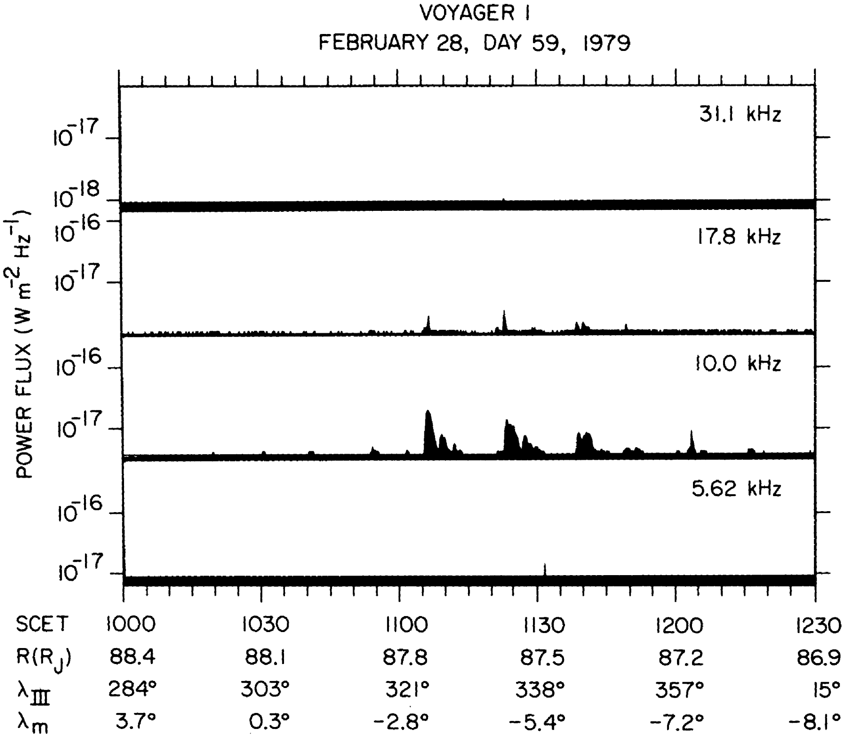

Fig. 2. The set of bursts shown in Figure 1 as viewed with the Voyager plasma wave spectrum analyzer.

four channels; the height of the black area corresponds to the signal intensity in the respective channel. The three prominent events of Figure 1 are quite evident in Figure 2, as are several other weaker events. The periodic occurrence discussed above is reflected in the weaker events. The amplitude profile is also evident in Figure 2 with the maximum power flux reaching about $2 \times 10^{-17}$ W m$^{-2}$ Hz$^{-1}$. One can also see that the bursts do not extend much above 20 kHz.

Having Figure 2 as a prototypical set of events, we proceeded to search the Voyager 1 and 2 spectrum analyzer data from the vicinity of Jupiter for similar sets of events. We looked for a series of periodically spaced bursts in the frequency range around 10 kHz where the bursts had durations of less than a few minutes and where the frequency

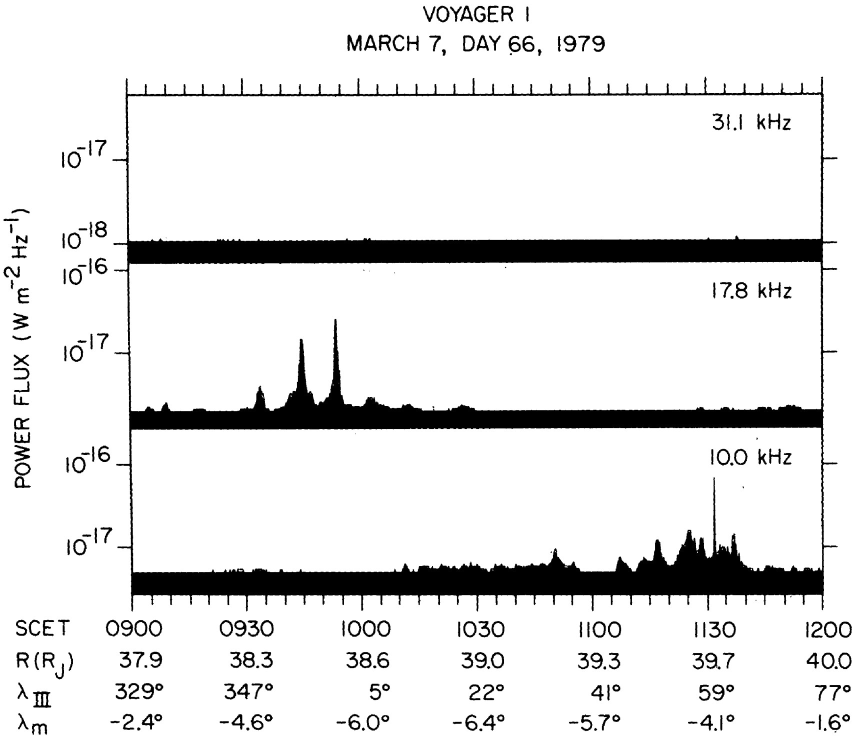

Fig. 3. An example of a series of radio bursts very similar to those shown in Figure 2, likely candidates for additional Jovian type III radio bursts.

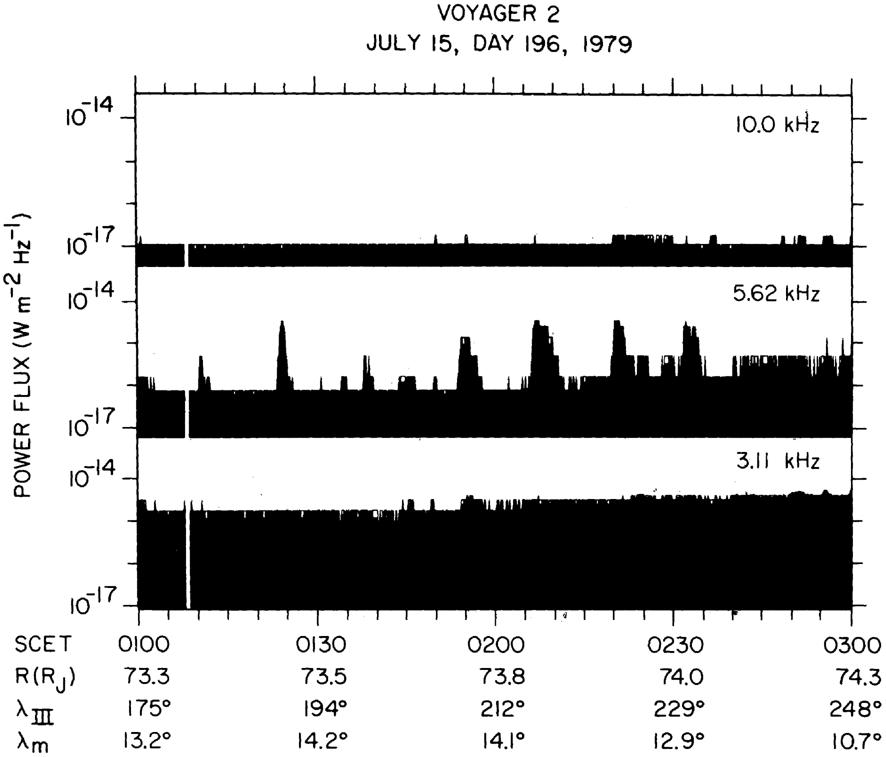

Fig. 4. A set of radio bursts observed by Voyager 2 in the early predawn sector. The Voyager 2 spectrum analyzer data suffers from a failure in the spacecraft data system which accounts for the staircaselike appearance of some of the bursts.

extent of the bursts was limited to three or fewer spectrum analyzer channels. The period of 16 min between bursts was a guideline for our search, but not so strict so as to preclude series with spacings of as little as 5 or as much as 30 min, should they occur. Unfortunately, the lack of waveform data for candidate events found in the spectrum analyzer data makes it virtually impossible to compare the important frequency-time characteristics with the type III model.

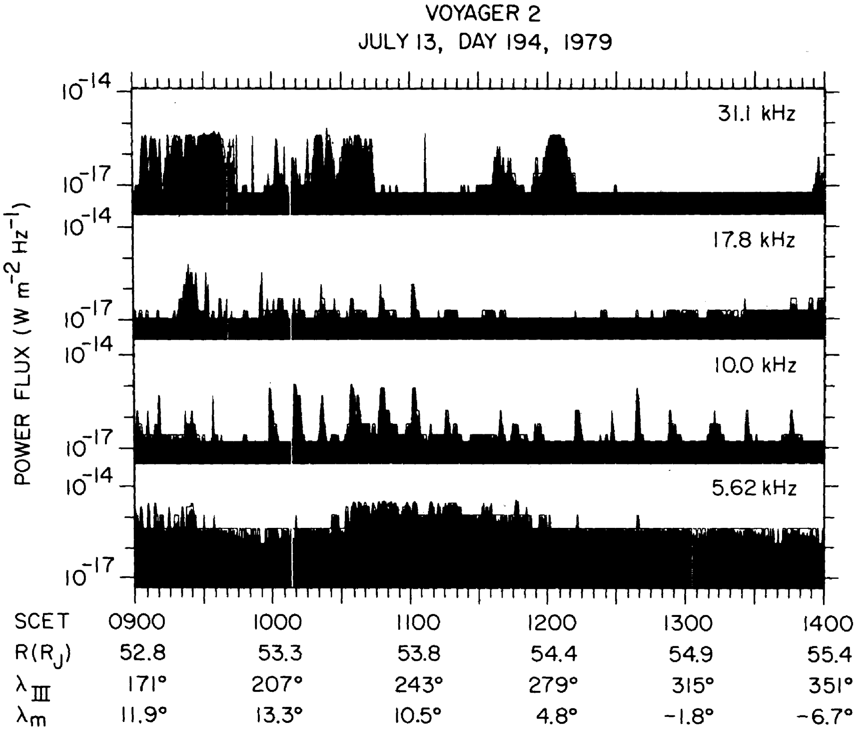

Fig. 5. An additional set of bursts observed by Voyager 2, again in the early morning sector. This is the longest series of bursts observed.

Figures 3–5 show additional sets of bursts which have appearances similar enough to those in Figure 2 to suspect them as being the same phenomena. Waveform data is not available for these bursts. The bursts in Figure 3 occurred near 1000 SCET on March 7 and were observed by Voyager 1 at 17.8 kHz at a distance of about 38.5 $R_J$ near 3.5 hours LT. At this time the plasma frequency was generally less than 4 kHz while the cyclotron frequency was less than 1 kHz (based on Voyager plasma and magnetometer data obtained from the Planetary Data System). Waveform data are available at this time, but not above 12 kHz, hence they are not useful for this event. Like those in Figure 2, there are a few bursts which are quite prominent surrounded by several weaker events. The spacing in time of this set of events is roughly 10 min per burst, somewhat more frequent than those in Figure 2. There are also some bursts later in Figure 3 in the 10-kHz channel with periodicity similar to the other event; however, the existence of a more continuous component to this set of bursts makes it difficult to tell whether these are similar bursts or just intensifications of the continuum radiation. Inspection of the waveform data at this time near 10 kHz shows the narrow-band electromagnetic bands similar to those reported by *Gurnett et al.* [1983] but shows no evidence for bursts such as those in Figure 1.

Figures 4 and 5 are from Voyager 2. The stairsteplike changes in amplitude noticed in these plots are a result of the recalibration due to a failure in the spacecraft data system. The fact that the amplitudes of the bursts in these two figures are about a factor of 10 greater than those in the two Voyager 1 examples is not considered to be a reliable difference, for the same reason. The bursts in Figure 4 occur between 0100 and 0230 SCET on July 15, 1979, and are confined to the 5.62-kHz channel. At this time the spacecraft was outbound at a distance of about 74 $R_J$ at 2.3 hours LT and was in the tail lobe; the plasma frequency was less than 100 Hz (based on the lower-frequency cutoff of continuum radiation), and the cyclotron frequency was about 200 Hz. These bursts have a spacing of about 14 min. The bursts in Figure 5 occur between 1000 and 1400 SCET on July 13 and are primarily at 10 kHz but extend to 17.8 kHz between 1000 and 1100 SCET. The spacing of the bursts in Figure 5 is about 14 min, although some variation over the interval is apparent. This interval appears to be the most extensive of those found. Voyager 2 was outbound at about 54 $R_J$ in the local post-midnight sector during these observations. Here the plasma frequency is less than 500 Hz (based on the continuum radiation cutoff), and the cyclotron frequency is about 400 Hz.

The events shown in Figures 2–5 represent all of the candidates for Jovian type III bursts found in this study. The set should not be construed as the result of a complete, rigorous search; there may be other cases. However, the signatures we looked for, including burst duration and periodicity, are not very restrictive and taken at face value could include many other intervals which may or may not be similar types of events. Certainly left out of this survey would be single or pairs of occurrences of the bursts that do not allow the periodicity restriction to be met. Further candidates are confused by the presence of other radio emissions, making identification with any certainty very difficult.

*Kurth* [1986] reported a rapidly downward drifting burst of radio emission observed in the Jovian magnetosphere at about 32 $R_J$ on the dayside which was associated with the intensification of continuum radiation in relatively narrow bands at about 6 and 9 kHz. The wideband data for the time interval surrounding this event is shown in Plate 2. The frequency-time appearance of the burst near 2319:20 SCET is similar to those of Figure 1. A second event is seen at about 2317 SCET in Plate 2. The downward sweep of the earlier burst is also similar to the primary burst in Plate 1. These bursts are not included in our catalog of events, owing to a lack of more than two bursts in sequence and their close spacing in time, but are obviously candidates because of their frequency-time appearance. Further, the intensification of the continuum radiation associated with the second burst in Plate 2 raises some very interesting questions about the relationship between the bursts and the continuum radiation.

## DISCUSSION AND CONCLUSIONS

The identification of radio bursts with a striking resemblance to solar type III radio bursts strengthens the similarities of Jupiter with a stellar object. That the unique frequency-time characteristics of the solar bursts can be reproduced in miniature, as it were, at Jupiter suggests similar mechanisms are proceeding in the vicinity of Jupiter as in the solar wind inside of 1 AU. Further, the similarity will allow us to utilize our understanding of how solar type III radio bursts are generated in order to speculate on the generation of the Jovian bursts.

The generally accepted explanation for solar type III radio bursts is based on the emission of energetic electrons from solar flares. These energetic electrons stream outward into the solar wind and, in the presence of the slower solar wind plasma, form an unstable two-stream instability. The instability is responsible for the generation of electron plasma oscillations or Langmuir waves at the local solar wind electron plasma frequency, $f_p$. While there are variations in the theory, most agree that the Langmuir waves can interact via nonlinear wave-wave processes to produce electromagnetic waves at either $f_p$ or $2f_p$.

The downward sweep in frequency of solar type III bursts, then, is a direct result of the Langmuir waves being produced at lower and lower frequencies as the energetic electrons pass through regions of ever decreasing plasma density. The increased duration at lower frequencies is due in part to the fact that velocity dispersion in the energetic electrons spreads the time interval over which the beam moves through a given shell of constant plasma frequency. The $r^{-2}$ dependence of the solar wind density also means the scale height for radial density variations is longer at larger distances, also adding to the longer durations at later times (lower frequencies) in an event.

Drawing upon the solar example, we would suppose that the Jovian magnetosphere is the source of energetic electrons which move outward through a density gradient. The lower-frequency range of the Jovian emission means the source region has a plasma frequency of about 10 kHz or a density of about 1 $\mathrm{cm}^{-3}$. The shorter duration of the events implies the scale size of the source region is smaller than in the solar wind and that the velocity dispersion has less of an effect because of shorter distances from the source of the particles to the generation region.

We have checked for observations of energetic electrons associated with the bursts presented in Figures 2–5 (B. H. Mauk, personal communication, 1987) and found no obvious correlations. This, however, is not very surprising since the waves observed are electromagnetic and probably have traveled a long distance from their source. The energetic particles would only have to traverse the source region and may never be observed at the spacecraft.

There are large volumes of space in the Jovian magnetosphere with densities of the order of 1 $\mathrm{cm}^{-3}$ [*Gurnett et al.*, 1981], so it is not straightforward to speculate on a location of the radio burst source. We can perhaps derive some insight as to the source location of the emissions by noting the location of the observing spacecraft for the events discussed above. The examples all occurred within a radial distance range of about 30–90 $R_J$. The outer distance could represent an upper limit on detectability due to increasing distance to the source. The inner limit is likely related to the passage of the spacecraft through plasmas with densities high enough to prevent observation of the emissions since radio waves can not propagate below the electron plasma frequency. Examples are found both on the dayside and on the nightside, indicating that there is no obvious local time dependence. Further, the observed events occur at system III longitudes as diverse as 0°, 210°, 245°, and 340°, implying no strong correlation with longitude or magnetic latitude. Hence we suspect the source region is near the middle magnetosphere, but more precise localization is not possible simply from these geometrical considerations.

Using the analogy with the sun, one may consider some possible consequences of the frequency-time character of the radio bursts. We postulate a beam of electrons with maximum energy at 50 keV (with no a priori reason for choosing this energy). By looking at the leading edge of the primary burst in Plate 1, we observe a maximum delay at the lower-frequency portion of the burst of about 5 s from the beginning of the burst near 11 kHz. If we assume half of the electron energy is in the direction parallel to the magnetic field (pitch angle about 45°), then the electrons will travel about 7 $R_J$ over the 5 s. This would imply a source region of extending about 7 $R_J$ in the direction parallel to the magnetic field. A similar calculation with a less energetic beam of 5 keV yields a distance traveled in 5 s of about 2 $R_J$. Such a distance is more compatible with a source in the inner magnetosphere possibly associated with the Io torus, as will be discussed below. Since typical plasma temperatures in the dayside middle magnetosphere at Jupiter are of the order of 100 eV to 1 keV, it would be reasonable to assume a beam energy of at least several keV, otherwise the beam would be buried within the bulk of the electron distribution and would be stable to the generation of plasma oscillations.

Another feature the model should address is the periodicity observed in the bursts. In 15 min a 5-keV electron with a pitch angle of 45° will travel of the order of 400 $R_J$. Should bouncing electrons be responsible for the 15-min periodicity, the source of the electrons would have to be in the distant magnetotail. The periodicity within an event (e.g., Plate 1) is easier to deal with, since the distance traveled by a similar electron is only about 60 $R_J$ in 2.5 min. It seems clear that both periodicities are probably not explainable with simple particle motions unless the source field lines extend to large distances in the magnetosphere.

An alternate tack is to ask what energy electron takes 15 min to execute a bounce motion in the magnetosphere. We select a field line dimension of about 100 $R_J$, which is the order of the size of the magnetosphere on the dayside. The implied velocity translates to an energy of about 200 eV. We conclude that this energy is too low to provide a positive free energy source to drive the Langmuir waves. More energetic electrons must be involved, and the bounce period of the electrons is probably not related to the 15-min periodicity of the radio emission.

It is possible that the periodicities noted in the events may be explained in ways other than electron bounce periods and may provide additional clues as to the source of the emissions. The approximate 15-min periods observed between bursts is very similar to the time for an Alfvén wave to propagate from the ionosphere in one hemisphere to the ionosphere in the opposite hemisphere through the Io plasma torus [*Bagenal and Leblanc*, 1988]. It is tempting to suggest that disturbances launched as Alfvén waves in the torus might excite the radio bursts. As the disturbance leaves the high-density torus for higher latitudes, it is possible that plasmas with the required density would be traversed. This model has the added feature that the multiple bursts observed in the Plate 1 event could be related to multiple reflections between the ionosphere and the torus. These multiple reflections have been suggested already by *Wright* [1987].

A model based on Alfvén waves in the Io torus caused by the motion of Io through the plasma might suggest that the position of Io is important in determining burst variability, although models of these Alfvén waves [*Bagenal and Leblanc*, 1988] suggest that they are distributed over large ranges of longitude trailing Io. For the activity shown in Figures 2–5, the system III longitude of Io (i.e., the sub-Io longitude in system III) is in the range of about 70°–170°. This reasonably tight range of longitudes represents the most restrictive geometric variable associated with the bursts and adds credence to an Io connection. This range does not correspond well to the active sector predicted by the magnetic anomaly model [*Vasyliunas and Dessler*, 1981]. It is unclear, however, how the position of Io in longitude might be important to the radio emission generation mechanism. Longitudinal density variations would seem to be a local variation to consider, though. Contrary to intuition, the phase of Io as viewed by the spacecraft appears to be unimportant in determining the visibility of the bursts since the examples studied herein occur with a wide range of the spacecraft-Jupiter-Io angle.

While we have shown reasons to expect that Io or the Io torus may be important in the generation of this new set of Jovian radio emissions, the notion is quite speculative, and no solid model for the generation of the waves exist at this time. It is unlikely that the limited data set available from Voyager will provide a definitive solution to the generation mechanism or source location for the Jovian type III radio bursts. The Galileo mission, with its long orbital phase, will likely be required to provide the additional data required to fully understand the origin of these waves.

*Acknowledgments.* We are indebted to B. M. Mauk for providing information on energetic particle fluxes observed by the Voyager LECP instrument during the events studied herein. We acknowledge the use of Voyager plasma and magnetometer measurements obtained through the Planetary Data System for the calculation of electron plasma and cyclotron frequencies used herein. We (W.S.K. and D.A.G.) regret that Fred Scarf was unable to see this work through to its completion. Nevertheless, we are grateful for his participation in the earlier stages of this study as well as his excellence in leading the Voyager plasma wave investigation until his untimely death in July 1988; his contributions will be sorely missed. The research at the University of Iowa was supported by NASA through contract 957723 with the Jet Propulsion Laboratory. The research at TRW was supported by NASA through contract 957805 with the Jet Propulsion Laboratory.

The Editor thanks C. H. Barrow and another referee for their assistance in evaluating this paper.

## REFERENCES

Bagenal, F., and Y. Leblanc, Io's Alfvén wave pattern and the Jovian decametric arcs, *Astron. Astrophys.*, *197*, 311, 1988.

Bridge, H. S., et al., Plasma observations near Jupiter: Initial results from Voyager 1, *Science*, *204*, 987, 1979.

Burke, B. F., and K. L. Franklin, Observations of a variable radio source associated with the planet Jupiter, *J. Geophys. Res.*, *60*, 213, 1955.

Gurnett, D. A., F. L. Scarf, W. S. Kurth, R. R. Shaw, and R. L. Poynter, Determination of Jupiter's electron density profile from plasma wave observations, *J. Geophys. Res.*, *86*, 8199, 1981.

Gurnett, D. A., W. S. Kurth, and F. L. Scarf, Narrowband electromagnetic emissions from Jupiter's magnetosphere, *Nature*, *302*, 385, 1983.

Kaiser, M. L., and M. D. Desch, Narrow-band Jovian kilometric radiation: A new radio component, *Geophys. Res. Lett.*, *7*, 389, 1980.

Kurth, W. S., Plasma waves and continuum radiation in planetary magnetospheres, in *Comparative Study of Magnetospheric Systems*, edited by B. M. Pedersen et al., p. 497, Cepadues-Editions, Toulouse, France, 1986.

McCulloch, P. M., and G. R. A. Ellis, Observations of Jupiter's decametric radio emissions, *Planet. Space Sci.*, *14*, 347, 1966.

Ness, N. F., M. H. Acuña, R. P. Lepping, L. F. Burlaga, K. W. Behannon, and F. M. Neubauer, Magnetic field studies at Jupiter by Voyager 1: Preliminary results, *Science*, *204*, 982, 1979.

Scarf, F. L., and D. A. Gurnett, A plasma wave investigation for the Voyager mission, *Space Sci. Rev.*, *21*, 289, 1977.

Scarf, F. L., D. A. Gurnett, and W. S. Kurth, Jupiter plasma wave observations: An initial Voyager 1 overview, *Science*, *204*, 991, 1979.

Vasyliunas, V. M., and A. J. Dessler, The magnetic anomaly model of the Jovian magnetosphere: A post-Voyager assessment, *J. Geophys. Res.*, *86*, 8435, 1981.

Warwick, J. W., et al., Voyager 1 planetary radio astronomy observations near Jupiter, *Science*, *204*, 995, 1979.

Wright, A. N., The interaction of Io's Alfvén waves with the Jovian magnetosphere, *J. Geophys. Res.*, *92*, 9963, 1987.

Zabriskie, F. R., Low-frequency radio emission from Jupiter, *Astron. J.*, *75*, 1045, 1970.

---

D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

(Received December 1, 1988;
revised January 18, 1989;
accepted January 20, 1989.)