the same radiation is being detected in both regions.

If the continuum radiation cutoff does extend down to as low as 30 Hz in the predawn region, this cutoff would imply densities as low as 1.0×10^{-5} cm^{-3}. Such low densities on the nightside of Jupiter strongly suggest that the spacecraft is entering a region comparable to the tail lobe of Earth's magnetosphere, which is nearly devoid of plasma. In fact, comparisons of dayside and tail-lobe spectra of continuum radiation in Earth's magnetosphere (*10*) show a strikingly close resemblance to the spectra in Fig. 6, the only essential difference being that the continuum radiation is more intense at Jupiter and extends down to lower frequencies. Although the intense broadband emissions detected on the outbound pass through the tail almost certainly consist of continuum radiation, other narrowband emissions are also known to occur near the low-frequency cutoff of the continuum radiation. At the time of this writing, we have not received sufficient wideband data to adequately investigate the origin of these narrowband emissions.

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26 September 1979

Planetary Radio Astronomy Observations from Voyager 2 Near Jupiter

Abstract. *The Voyager 2 Planetary Radio Astronomy experiment to Jupiter has confirmed and extended to higher zenomagnetic latitudes results from the identical experiment carried by Voyager 1. The kilometric emissions discovered by Voyager 1 often extended to 1 megahertz or higher on Voyager 2 and often consisted of negatively or, less frequently, positively drifting narrowband bursts. On the basis of tentative identification of plasma wave emissions similar to those detected by Voyager 1, the plasma torus associated with Io appeared somewhat denser to Voyager 2 than it did to Voyager 1. We report here on quasiperiodic sinusoidal or impulsive bursts in the broadcast band range of wavelengths (800 to 1800 kilohertz). A Faraday effect appears at decametric frequencies, which probably results from propagation of the radiation near its sources on Jupiter. Finally, we discuss the occurrence of decametric emission in homologous arc families.*

On 9 July 1979, Voyager 2 carried the second low-frequency radio receiver (*1*) to be flown into Jupiter's environment. The experiment was virtually identical to that carried past Jupiter by Voyager 1 (*2*) on 5 March 1979, notable differences being the higher zenomagnetic latitudes of the approach trajectory, and the more distant encounter with Jupiter of Voyager 2. Our purpose here is, once again, to present selected results related to these differences and to some of the many phenomena we could only mention in the earlier report (*2*).

As our familiarity with radio Jupiter has grown in the months since the Voyager 1 encounter, we have found it necessary to review some of our preliminary ideas, especially with respect to the source or sources of the kilometric wavelength (KOM) radiation. We concluded (*2*) that the coincidence of the observed wave frequencies of KOM with the plasma frequencies observed in the Io torus provided an argument in favor of the torus as the source of KOM. We have often seen on Voyager 1 and 2 instances of "KOM" radiation extending to much higher frequencies than the 500 kHz of a typical event, often to 1 MHz and above. As we shall see, the Io torus was probably more dense than at the time of the Voyager 1 encounter, although it is not clear whether the increased torus density can support radiation as high as 1 MHz. Furthermore, at

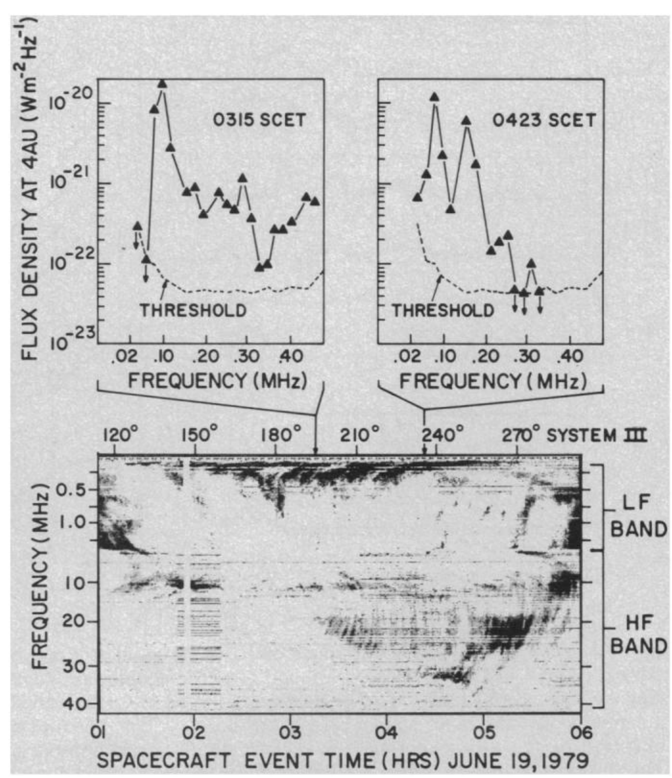

Fig. 1. Dynamic spectrum of Jupiter's radio emissions observed by the Planetary Radio Astronomy (PRA) instrument on Voyager 2. The total received power in each of the 198 frequency channels is shown as a function of spacecraft event time (*SCET*) and sub-Voyager Jupiter longitude [system III (1965)]. Increasing power is indicated by increasing darkness. The PRA receiver is divided into (i) a 70-channel, low-frequency (*LF*) band between 1.2 kHz and 1.3 MHz with a 1-kHz bandwidth and (ii) a 128-channel, high-frequency (*HF*) band between 1.2 MHz and 40.5 MHz with a 200-kHz bandwidth. Between 0130 and 0500 SCET, a KOM event can be seen in the LF band extending from 0.04 to nearly 1 MHz. It is composed of numerous narrowband drifting structures. In the upper two panels, flux density spectra are shown at two different times, illustrating the intensity behavior of the KOM emission. In the HF band, an Io-A or main-"source" event with characteristic arc structure can be seen centered on 240° longitude.

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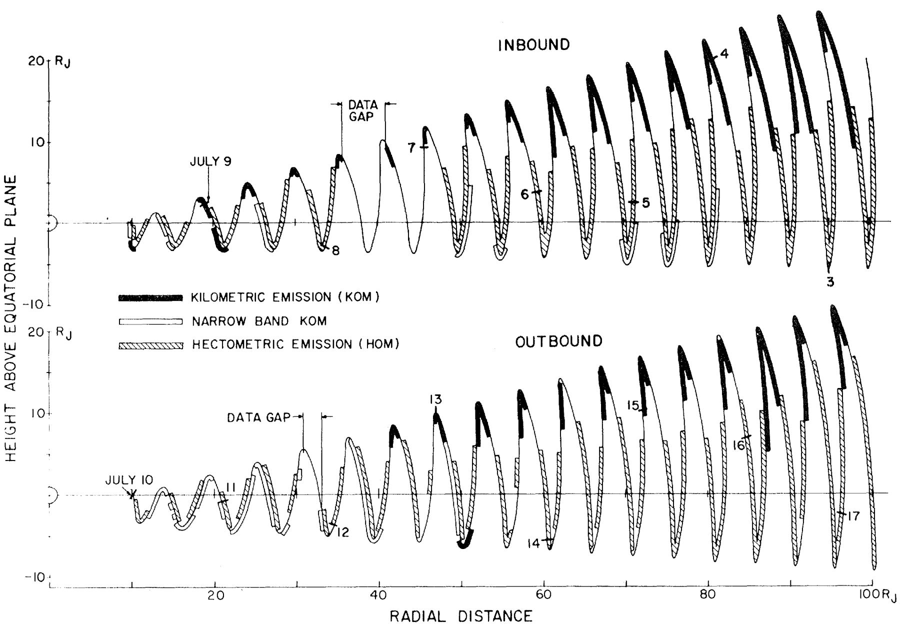
the time of the Voyager 1 encounter, Voyager 2, at 0.5 astronomical unit from Jupiter, detected extremely intense KOM events. Voyager 1 spent about 10 hours in the torus, covering about 250° in longitude. If the KOM source were in the plasma torus, Voyager 1 might well have encountered very large electric fields as implied by the (remote) Voyager 2 observations. However, the observed in situ field strengths fall far short of these large values. Although not conclusive, this result presents a problem for the torus as a possible KOM source region. We also suggested that KOM could possibly originate high above the auroral zones. This now seems unlikely, because the only known characteristic frequency at 1 MHz in this region is the electron gyrofrequency. In order to emit simultaneously over a bandwidth of 1 MHz down to 20 kHz or below at the gyrofrequency, the source region would extend over several Jupiter radii.

We now believe that the region of the Io torus footprint on Jupiter's ionosphere may be an alternative site for KOM, aside from the torus itself. It is known to be associated with intense particle precipitation (*3*) and, in analogy with Earth's auroral zone, probably contains many regions of very large electric field strength. Escaping emission from the auroral ionosphere would probably be in the ordinary mode and would match the observed left-hand polarized KOM from the northern hemisphere. Alternatively, KOM from the torus's northern hemisphere would be in the extraordinary mode.

Figure 1 shows an example of KOM seen by Voyager 2. Its general properties resemble those we described for Voyager 1, but additional characteristics are now evident on this and other Voyager 2 events. A number of events show low-frequency cutoffs greater than 100 kHz. Thus, the solar wind or Jupiter magnetosheath are excluded as cutoff media because their electron densities fall far short of the requisite, ≥ 100 cm^{-3}; the torus itself could be responsible. The KOM events often contain narrowband fine structure, drifting negatively or positively. These narrowband features drift to higher or, more often, lower frequencies with drift rates of 4 to 10 kHz/min at frequencies near 100 kHz. We do not know what causes these drifts, although their similarity in some respects to solar drifting bursts suggests motion of a source region with physical properties that vary sharply with distance.

We have found an additional form of KOM in both the Voyager 1 and 2 data. The more familiar form is the kind of "tapered" KOM event discussed in our Voyager 1 report [figure 2 in (*2*)] and illustrated here in Fig. 1. The other form is of much narrower bandwidth (typically 40 to 80 kHz), is confined to the 60- to 150-kHz frequency range, and displays no evidence of systematic variations in duration with increasing frequency. Narrowband KOM has a waveform that often consists of bursts of long duration, slow buildup and decay, and relatively little fine structure.

We have found it instructive to plot the occurrence of all the low-frequency events, including hectometric (HOM)



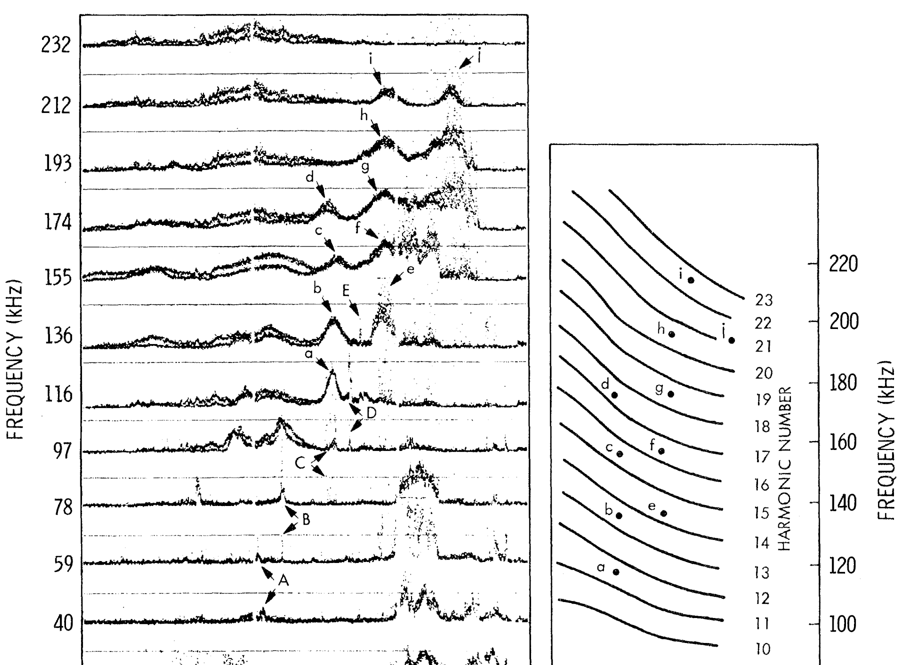


Fig. 2 (top). A plot of the occurrences of Jupiter's kilometric and hectometric emissions for the period of 4 to 17 July 1979 as a function of the position of Voyager 2 with respect to the magnetic equatorial plane. The kilometric radiation is further divided into narrowband and tapered events, the latter shown by a heavy line. Fig. 3 (bottom). The plasma resonances observed by the PRA experiment near the time of closest approach of Voyager 2 to Jupiter. The spikes indicated by uppercase letters in the left-hand panel are interpreted as upper hybrid resonance emission. The broader and smoother peaks indicated by lowercase letters are believed to be $(n + 1/2)$ harmonics of the electron gyrofrequency. The curves in the right-hand panel represent local gyrofrequency harmonics of integral order n as functions of time as derived from the magnetometer data; letter points are keyed to corresponding peaks in the other panel.

emissions, near Voyager 2's closest approach on "wiggle" diagrams, in which the magnetic equator of Jupiter is held constant, while the spacecraft oscillates up and down across it (Fig. 2). Several important features of HOM and KOM radiation thereby become immediately apparent. Inbound and outbound, Voyager 2 saw KOM tapered events almost exclusively north of the zenomagnetic equator rather than south of it; this might correspond to the greater northerly latitudes of the spacecraft. However, the southerly excursions outbound for the first several Jupiter rotations are as far south as the most northerly excursions before or after closest approach, but they show no tapered events. Furthermore, there is a strong tendency on the northern side and a tendency on the southern side for tapered events to occur at relatively lower latitudes as the spacecraft move farther from Jupiter. Especially on the inbound leg, tapered events occur most frequently at a constant 8 Jupiter radii (R_J) above the equatorial plane. The southern events at all times (except one) appear to be narrowband events unlike the multifrequency tapered events. Both inbound and outbound, there is a strong tendency for the KOM events to be centered before dipole tip passage (that is, inbound); the right-hand sides of the peaks of the wiggle diagram show emission closer to the equator than the left-hand sides (outbound). In fact, there is a striking absence of any KOM tapered events for five rotations after closest approach. Finally, HOM appears strongly in the equatorial plane, almost exclusively to the KOM tapered events.

At its closest approach, Voyager 2 was 10 R_J from Jupiter and did not penetrate the "core" of the torus. We did not observe the same full sequence of gyroharmonic and plasma emissions as we did on Voyager 1. However, we see intense emissions when Voyager 2 is near the planet and close to the magnetic equator. There seem to be either isolated spikes (with time variations less than 6 seconds) or smooth, symmetrical unpolarized peaks lasting between 30 minutes and more than an hour. These two kinds of emission are similar to those Voyager 1 observed in the torus and can be similarly interpreted, that is, as emissions near the upper hybrid frequency and ($n + 1/2$) harmonics of the gyrofrequency. These or similar emissions are very rarely, or never, observed outside the close encounter.

Tapered events are also spiky, but in a different way. In particular, the association between smooth and isolated spiky emission, obvious on both Voyager 1 and 2 in near encounter, is not observed in the tapered events. Figure 3 shows these two types of emissions and, at still lower frequencies, a third component, probably of different origin. Figure 3 also shows the computed values of the gyroharmonics, based upon the magnetometer experiment's measurements (*4*) during the Voyager 2 encounter and the peaks of the smooth emissions, which mostly fall well between the gyroharmonics. Note that the "gyroharmonic" peaks, as we have identified them, differ among themselves in timing and shape. The gyrofrequency is about half the channel spacing (19.2 kHz) between our adjacent reception channels. A peak observed on one channel is therefore always two harmonics away from a peak on the adjacent channel. The excitation of the gyroharmonics apparently occurred episodically, just this once inbound during Voyager 2 encounter and not at all outbound. Our Voyager 1 data suggest that the physical conditions for plasma excitation were then variable in such a way as to produce a nonuniform visibility of the plasma line. If the spiky emissions accompanying the gyroharmonics are produced at the upper hybrid resonance, as was the case on Voyager 1 (*2*), we can determine the electron density at the time of Voyager 2's closest approach to Jupiter. Its maximum value occurred near 2300 hours spacecraft event time (SCET) on 9 July 1979 and was 450 cm^{-3}. This corresponds to a measured upper hybrid resonance that occurs in our 193 kHz channel. If this interpretation is correct, the plasma torus expanded between the Voyager 1 and 2 encounters. An alternate view has been developed by the Plasma Wave team (*5*), who interpret the emissions near 59 kHz

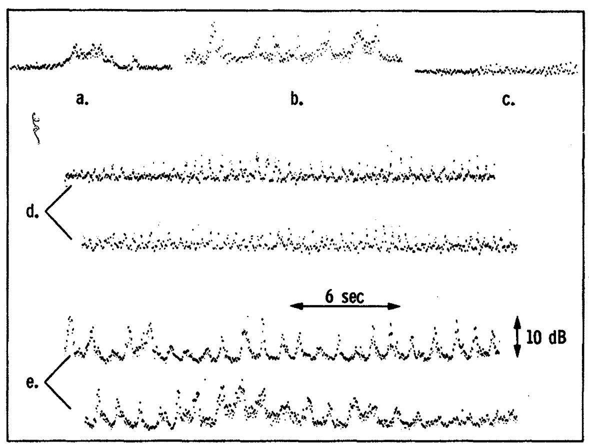


Fig. 4. Fixed-frequency records made with 30-msec time resolution and in strips as long as 24 seconds (d and e). Examples (a) and (c) were obtained at a frequency of 1449 kHz; all others are at 1192 kHz. These quasi-periodic emissions are unpolarized; their phase and frequency are variable across any one of these strips. This variability suggests emissions not created by interference aboard the spacecraft. Panel (a) shows an *L* burst, that is, a burst lasting longer than 2 seconds. As seen in Jupiter's emission from the ground, bursts like this one are classically interpreted to be a result of interplanetary scintillation. The spacecraft here was only 0.5 astronomical unit from Jupiter, thus suggesting that Jupiter also produces bursts on a scale of seconds.

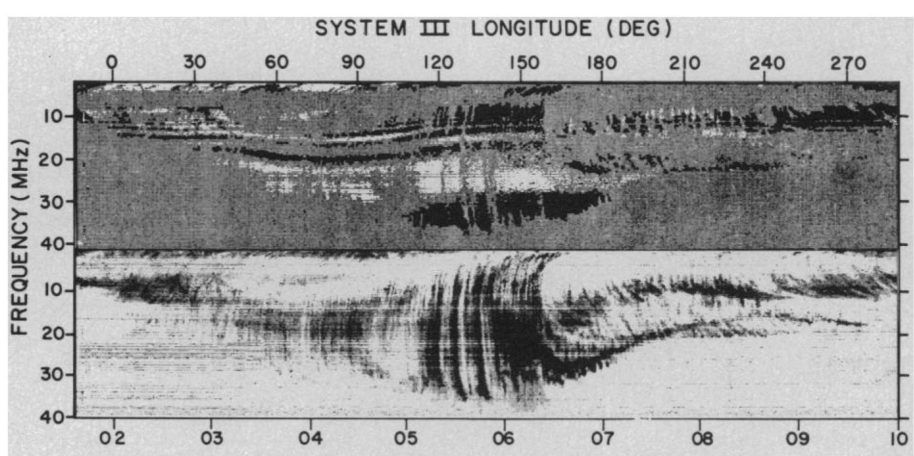


Fig. 5. The lower panel shows a total power dynamic spectrum covering the PRA high-frequency band. Io reached a phase angle of 90° at about 120° system III longitude (0530 SCET), so this geometry corresponds to a classic Io-B or early-"source" event, with maximum frequency reaching the fabled 39.5 MHz. The upper panel is a version of the lower panel that shows only the sense of polarization (LH white and RH black). The obvious changes in polarization as a function of frequency which are seen in the upper panel apparently are not manifested in the total power plot shown in the lower panel. The sharp, randomly spaced lines parallel to the time axis are artifacts.

to be the upper hybrid resonance at closest approach.

On both spacecraft, we have carried out observations at fixed frequencies in a special mode in which samples are acquired at 30-msec intervals. We have often found, at frequencies in the range 800 to 1800 kHz (the highest at which we have been able to implement the observations effectively), very short but quasi-periodic emissions (Fig. 4). These often are burstlike with quasi-periods of the order of 1 second more or less and with spikelike peaks probably shorter than 30 msec but reaching to very high flux densities. We saw these bursts for more than a year as the spacecraft approached Jupiter. The bursts are polarized, usually in the right-hand (RH) sense. They may represent low-frequency phenomena associated with the "S" bursts (that is, millisecond bursts) famous among ground-based decametric wavelength observers of Jupiter.

The plasma density in the torus, combined with the magnetic field there, requires that a substantial Faraday effect must occur as decametric, or longer, wavelength waves propagate through it. Given the Voyager 1 model of electron densities in the torus (*2*), the predicted rotation of a wave at 10 MHz is ~ 25 radians; this varies inversely as the square of the frequency for the usual and familiar quasilongitudinal Faraday effect. In this phenomenon, an incident wave of arbitrary polarization breaks down into two separate characteristic waves with circular polarization in opposite senses. If the incident wave is elliptical, the axes of the ellipse will rotate as the phase difference between the characteristic waves changes. Finally, wave propagation in the torus is, for all practical purposes, entirely quasilongitudinal for decametric emission.

Figure 5 shows an early-source radio event that, incidentally, reaches to a frequency of about 39.5 MHz, as high as any we've seen with either spacecraft and as high as the highest seen in ground-based data. From about 10 to 23 MHz, the spectrum of polarization (upper panel) shows distinctive fringes strongly reminiscent of Faraday fringes often seen in ground-based Jupiter data. A computation assuming that these are quasilongitudinal Faraday effects in the torus is successful in the sense that the fringes have the correct spacings in frequency to be interpreted in that way. However, we believe this would be an incorrect calculation ultimately because the fringes appear in the polarized spectra. The planetary radio astronomy (PRA) antennas are elliptically polarized, for an arbitrary propagation direction, in opposite senses in the RH and LH (left-hand) channels but with their major axes parallel. If the wave falling on this antenna system were elliptically polarized with axes rotating as a function of frequency, we would see modulation peaks in the intensity spectrum (lower panel) as the major axis of the incident ellipse becomes simultaneously parallel to the major axes of the RH and LH ellipses produced by the antenna system (*6*). The polarization spectrum, which is the difference of the RH and LH spectra, should show no modulation inasmuch as the modulation on the RH and LH channels is inphase and equal in amplitude. The actuality is precisely opposite to what we have just described for the quasilongitudinal Faraday effect acting on an elliptical wave. We believe that the axial ratio and sense of polarization vary as functions of frequency during those periods when fringes appear on the polarization spectra. This effect, incidentally, is common throughout our data. A possible explanation is in terms of a different kind of Faraday effect than the quasilongitudinal or quasitransverse ones familiar to ionospheric physicists (*7*). Such an explanation—called *Y*-one Faraday effect because the parameter *Y*, the electron gyrofrequency in units of the wave frequency, is of order unity—was given in (*6*), for similar polarization reversals observed with the Boulder polarimeter. In that explanation, the radio source region is necessarily very near Jupiter because only there will 20 MHz waves be in a region for which, say, $0.3 \leq Y \leq 3$. Furthermore, the wave generated by the source is not at that time in a characteristic (elliptical) mode since it is necessary for the wave to split into the two characteristic modes before the effect can occur. Under these restrictions, the polarization sense reverses. The source is not a quasitransverse region; if it were, the polarization "lanes" (Fig. 5) would be exactly symmetric between RH and LH states. Instead the lanes are clearly asymmetric with RH stronger than LH during the most intense phase of the emission. Finally then we must combine the Faraday effect produced in the torus with the changing polarization ellipse incident on the torus. It appears that a deconvolution of this sort requires a precise knowledge of source location, since the source position deter-

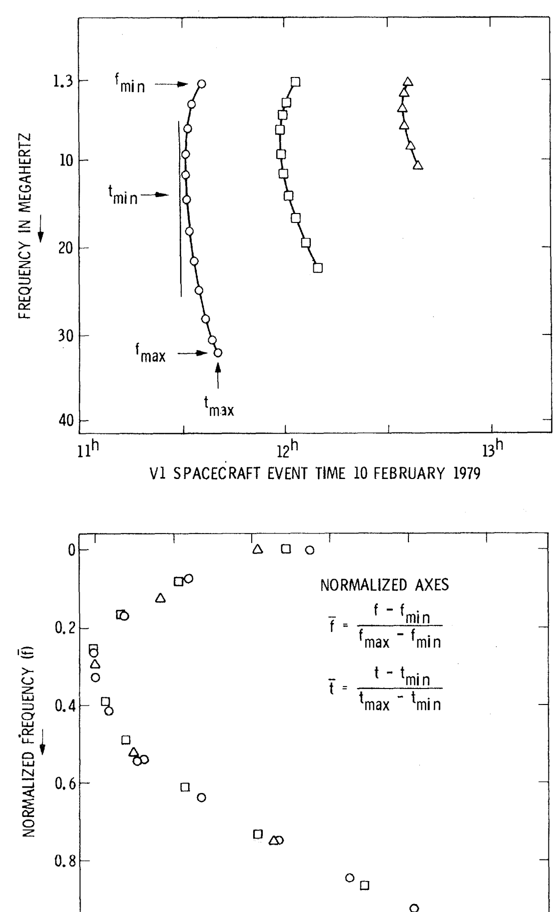


Fig. 6. The top panel shows a family of decametric arcs, at maximum extending to 32 MHz. The lower panel shows these three arcs replotted on normalized time and frequency coordinates. In this plot, the three arcs are virtually identical in shape.

mines critically whether the ray paths to the spacecraft intercept the torus.

Extraordinary arc structures continue to dominate the Voyager 2 high-frequency data as they did the data from Voyager 1. Figures 1 and 5 show the great arcs (extending to high frequencies) as they invariably appear in connection with Io-controlled early (Fig. 5) and main (Fig. 1) source emission. The great arcs in the early source have vertices early (that is, the arcs open toward increasing times) while those in the main (and late) sources have vertices late (arcs open toward decreasing times). This pattern is identical in sense to what was observed by Voyager 1 [figure 1 of (*2*)]. It argues strongly for a geometric origin of the arc shapes.

The systematics of the arc shapes is as remarkable as the longitudinal pattern of vertex-early and vertex-late great arcs. The arcs often occur in nested sets whose frequency range and curvature progressively change over times several hours long. In some of these nested sets (Fig 6) the arcs are homologous, in the sense that when they are plotted on normalized time and frequency coordinates they have virtually the same shape. Our study is still preliminary. Clearly, however, there exist homologous arc families, including arcs that extend from 1 MHz to well above 30 MHz, to those lying totally below 10 MHz. Individual arcs persist from less than 10 minutes to more than 1/2 hour. The description in terms of normalized coordinates (Fig. 6) can qualitatively be summarized by two facts: (i) arcs of longer duration extend to higher frequencies; and (ii) the higher the maximum frequency, the higher the vertex frequency.

We conclude that all decametric emission occurs when its instantaneous source lies in a single special geometrical relation to the observer; otherwise the very special shape is difficult to understand. Its sources lie at all longitudes because we see these arcs everywhere as Jupiter rotates, but each arc corresponds to a single source. Finally, the homologous members of a single family of arcs occur in sequences extending over 40 or more degrees of Jupiter longitude.

One simple model immediately suggests itself for these arcs. If (i) the radio sources produce emission in hollow conical sheets centered on a given line of force and (ii) the emission occurs at the local electron gyrofrequency, then, because the line of force is curved, different frequencies correspond to cones pointing in different directions. As Jupiter rotates, these cones, fixed relative to one another, rotate past the direction of the spacecraft. Simple geometrical considerations show how an arc will be formed for ad hoc choices of emission angle and the active line.

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Jupiter's Cloud Distribution Between the Voyager 1 and 2 Encounters: Results from 5-Micrometer Imaging

Abstract. *As part of a continuing effort of ground-based support for Voyager target selection, infrared images in the 5-micrometer wavelength region were acquired in preparation for the Voyager 2 flyby of Jupiter. Observations were made during May 1979 from the Palomar 5-meter telescope and the new 3-meter NASA Infrared Telescope Facility at Mauna Kea and are compared to previous observations. Variations seen in the 5-micrometer flux distribution suggest global patterns of clouding over of some Jovian belts and clearing of others. These data were used to predict the Jovian cloud distribution at the time of the Voyager 2 encounter in order to target the imaging and infrared experiments to areas free of high obscuring clouds.*

Over the past year a coordinated program of high spatial resolution infrared imaging of Jupiter was undertaken in order to support target selection for Voyager imaging and infrared experiments (*1*). The 5-μm wavelength region was used for this imaging because it is relatively free from Jovian gaseous spectral absorption lines and offers a view of the deepest observationally accessible layers of Jupiter's atmosphere (*2*). These deep holes in the atmosphere appear as isolated bright regions at 5 μm and are found to vary in position and spatial distribution with time (*3, 4*). Infrared observations leading up to the Voyager 1 encounter in March have already been reported by Terrile *et al.* (*1*) who discussed the changes observed between October 1978 and March 1979. We now describe the observations obtained after March as part of the target selection for the Voyager 2 encounter in July 1979.

Voyager 2 has a capability similar to that of Voyager 1 for retargeting observations to areas of high scientific interest. Voyager 1 imaging and infrared experiments (*5, 6*) were successfully targeted to observe some of the hottest infrared regions and thus the deepest areas in the Jovian clouds even though sequencing considerations required that targeting be established 1 month before encounter. This month-long time constraint was also present in the Voyager 2 planning and necessitated our making predictions of 5-μm activity and position at the time of encounter.

Observations were made from the Hale 5-m telescope at Palomar, Califor-

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