ing soon after closest approach. The peak plasma wave amplitudes were quite high (for example, near 1815 on 6 March, the 56- and 100-Hz wave levels ranged up to about 4 mV/m), and these waves, which have no analogs in Earth's tail region, are presently unidentified. The waves have some characteristics that suggest a relationship with continuum radiation.

This brief report touches on only a few aspects of the plasma wave observations near Jupiter. At the time of writing we had only received data records for a very small fraction of the actual wave-form observations, and the complete analysis of Jovian plasma physics will naturally involve study of all of these samples, as well as detailed correlations with measurements from other Voyager instruments.

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Voyager 1 Planetary Radio Astronomy Observations Near Jupiter

Abstract. *We report results from the first low-frequency radio receiver to be transported into the Jupiter magnetosphere. We obtained dramatic new information, both because Voyager was near or in Jupiter's radio emission sources and also because it was outside the relatively dense solar wind plasma of the inner solar system. Extensive radio spectral arcs, from above 30 to about 1 megahertz, occurred in patterns correlated with planetary longitude. A newly discovered kilometric wavelength radio source may relate to the plasma torus near Io's orbit. In situ wave resonances near closest approach define an electron density profile along the Voyager trajectory and form the basis for a map of the torus. Detailed studies are in progress and are outlined briefly.*

Low-frequency radio emissions from Jupiter have been observed from Earth for nearly three decades. These emissions showed that Jupiter had a strong magnetic field, that highly variable and intense waves were omnipresent near Jupiter, and that the satellite Io interacted strongly with Jupiter's magnetosphere. Nevertheless, the emission mechanisms, the locations of the sources, and detailed properties of the magnetospheric plasma are still unknown. The planetary radio astronomy (PRA) experiments on the Voyager 1 and 2 spacecraft were designed to study the low-frequency radio emissions from Jupiter both at a distance and in situ. The purpose of this report is to present selected results from the Voyager 1 PRA experiment near Jupiter closest approach on 5 March 1979.

The PRA instrument (*1*) consists of a radio receiver that steps in frequency from 40.5 MHz to 1.2 kHz and an orthogonal pair of 10-m monopole antennas connected to provide right-hand (RH) and left-hand (LH) polarization. The receiver is a superheterodyne in each of two bands, from 1.2 to 40.5 MHz (high frequency) and from 1.2 kHz to 1.3 MHz (low frequency), respectively. In 6 seconds the receiver step tunes at intervals of 307.2 and 19.2 kHz through the high- and low-frequency ranges, respectively; the corresponding bandwidths are 200 and 1 kHz. Each step alternates in polarization between RH and LH. The receiver operated in several other data modes under Voyager computer control, but most of the results reported here used the stepping mode.

In the high-frequency band, the most striking observation is the ubiquitous presence of nested families of arcs on the frequency-time plot (Fig. 1). Almost without exception, all of the observed emissions resolve into arcs or portions of arcs. A considerable fraction of this frequency range is covered in ground-based observations of Jupiter, but these arcs have not been seen before. The reason undoubtedly lies in the strong communications interference and ionospheric effects that typically plague almost all radio observations made at frequencies lower than 20 or 25 MHz. Above 20 MHz, only the high-frequency portion of the greatest arcs would be visible from the ground. The sense of frequency drift at high frequencies is a function of Jupiter longitude. The same functional relationship has previously been observed from the ground. The greatest arcs, covering the widest frequency range (over 30:1 at maximum), are consistently RH in polarization. The sense of curvature of the arcs reverses near longitudes 20° and 200° close to south and north dipole tip.

Below 12 MHz, emission appears quasi-continuously at all Jovian longitudes. The curvature of the arcs whose vertices are in this range is larger than those at higher frequency. The polarization appears to vary with longitude, in the sense that RH waves are most common when the northern tip of Jupiter's magnetic dipole is tilted toward the spacecraft, and LH, when the southern tip is.

Some of the arc structure extends into the low-frequency band, although because our receiver functions here in a greatly expanded frequency scale and with much greater sensitivity, it is more difficult to recognize. Voyager first detected Jupiter in this band in late 1977 (*2*).

Near closest approach, the emissions in all bands changed dramatically. Below 1 MHz, where the local plasma frequency may exceed the observing frequency, the changes may be associated with wave propagation effects. Above 10 MHz, however, another explanation is required. Perhaps source directionality or shadowing of the source is responsible. The similarity of the data before and after encounter, with essentially no changes in signal levels, suggests that radio emissions do not depend on the solar phase angle within the source regions.

A few months before encounter, we began to observe a distinct new radio emission from Jupiter and generally in the kilometric band. These emissions

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usually persist for about an hour, over bandwidths of several hundred kilohertz. For a given activity period, the stormlike activity tends to spread in isolated bursts covering a larger time interval at low frequencies than at high ones (Fig. 2). The low-frequency cutoff between the 59- and 40-kHz channels (Fig. 2) is typical, although emission sometimes extends into the 20-kHz channel. More than half of these storms lie within ± 40° of longitude 200°. There is a smaller concentration of activity around 20°.

The radiation at 200° is usually LH polarized. Total emission power, if we assume the source emits isotropically over 100 kHz, is roughly 10^{10} W. The peak flux density at Earth would be 10^{-19} W m^{-2} Hz^{-1}. Individual bursts within a storm display a wide range of duration and are often as short as we can measure, 6 seconds. We have found no correlation between the occurrence of these emissions and Io's orbital position.

The source of the kilometric radiation is of great interest, particularly since many of its properties lead us to believe it is distinct from the higher frequency hectometric and decametric emissions. Certainly the low-frequency nature of kilometric radiation, far below the characteristic frequencies of the magnetic fields and plasma near the planet, suggests a source location at distances beyond several radii of Jupiter (R_J). Candidate source locations would have to include auroral regions high over Jupiter's poles or, more probably, the high-density plasma torus encircling Jupiter near the orbit of Io. The in situ plasma measurements made by PRA during Voyager 1's passage through the torus have provided strong, although not entirely compelling, evidence that the Io torus may indeed be the source of kilometric radiation. More detailed work must be done, however, to determine if the correspondence between the frequency range of kilometric radiation and the characteristic frequencies of the plasma torus is more than just a coincidence.

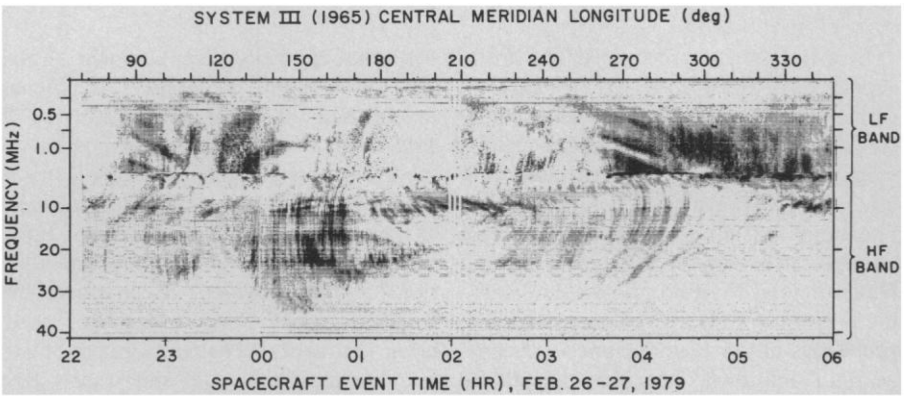

Fig. 1. Dynamic spectrum of Jupiter's low-frequency radio emissions. The total received power in each of the 198 frequency channels is shown as a function of time and sub-Voyager Jovian longitude. Increasing total power is indicated by increasing darkness. The occasional horizontal streaks are caused by spacecraft-generated interference. During this 8-hour interval, the phase of the satellite Io, with respect to the line of sight through the planet, ranged from 72° to 139°. The great arcs extending to frequencies as high as 32 MHz near 0400 correspond to the so-called Io-independent emission. Abbreviations: *LF*, low frequency; *HF*, high frequency.

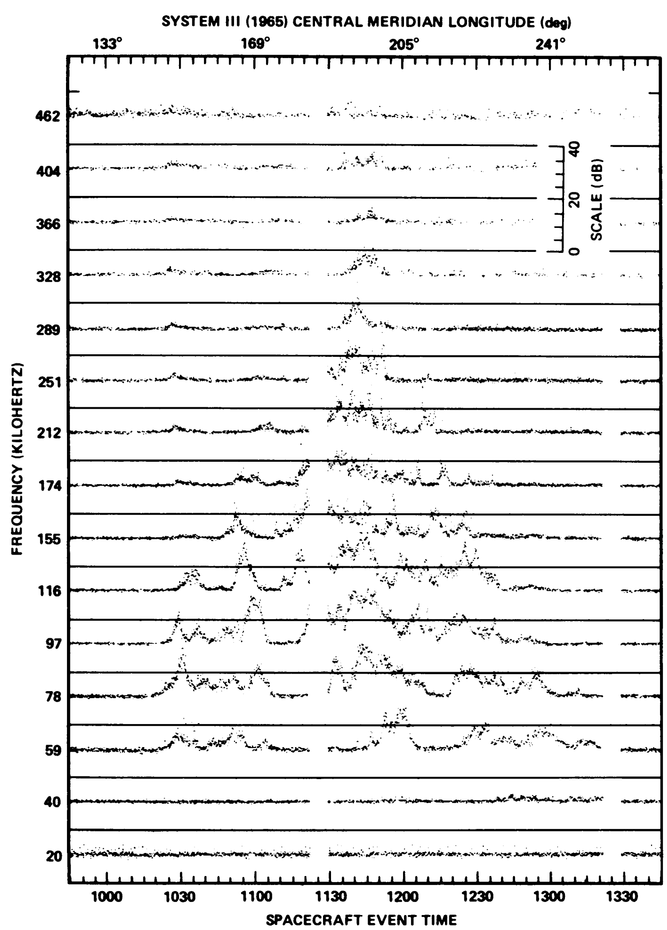

Fig. 2. An example of kilometer-wavelength emission from Jupiter. In the 4-hour interval shown, we plotted intensity against time at 14 frequencies between 20 and 308 kHz. Time resolution is 6 seconds. Kilometric emission characteristic of the events we have observed is evident at every frequency between 59 and 308 kHz; the emission persists over a much longer period of time at the lower frequencies. In this event there is a gradual decline in intensity with increasing frequency and a sharp cutoff in emission below 59 kHz. This, too, is characteristic of the events observed, although the lower cutoff frequency is somewhat variable. We attribute the gradual high-frequency falloff to the actual intensity spectrum of the radiation. The low-frequency cutoff is probably a propagation effect, however, and is not representative of the radiation mechanism. Individual bursts within this event range in duration from approximately 10 minutes to less than 6 seconds, the resolution limit. Note that the activity is centered on 200° sub-Voyager Jupiter longitude, statistically the most probable longitude range for observing kilometric wavelength emission. A dynamic spectrum of a similar event is shown in Fig. 1 from 0130 to 0230 between 75 and 250 kHz.

When the spacecraft was between 9 and 5 R_J, near the location where the Voyager ultraviolet spectroscopy experiment (3) demonstrated a "torus" of sulfur, the PRA spectra showed a strong narrow-band emission, drifting in frequency with time, in the range 20 to a few hundred kilohertz. We interpret this strong emission as natural noise near the ambient electron plasma frequency f_{pe} or, more precisely, near the upper hybrid frequency $f_{uh}{}^2 = f_{pe}{}^2 + f_{ce}{}^2$ (where f_{ce} is electron gyrofrequency). The main support for this interpretation is the observation of similar narrow-band emissions in Earth's magnetosphere by satellites crossing the plasmapause. The latter emissions are generally impulsive (4) and are often accompanied by intense emissions at frequencies separated by the electron gyrofrequency. Both kinds of emission are also visible in the PRA data (Fig. 3).

We show the variation of f_{pe} with time along the spacecraft trajectory in the top portion of Fig. 4. The main uncertainty comes from the difficulty sometimes encountered in determining the exact position of the upper hybrid resonance line. This amounts to perhaps no more than 20 or 30 percent of the electron density values given in Fig. 4 at the low density levels. Near closest approach, we derive f_{pe} from the observed f_{uh}, with the intensity of the magnetic field measured by the magnetometer experiment (5).

The density curve in Fig. 4 shows two main peaks around 0900 and 1500 spacecraft event time, when the spacecraft was close to 6 R_J from Jupiter's center; this is strong evidence for an increase in the electron density at Io's orbit.

The peak at 0900 spacecraft event time has fine structure, but, in this first approach, we ignored these rapid variations and drew an average curve through the experimental points (Fig. 4). We also assumed that there are no longitudinal variation effects or effects immediately in Io's vicinity, in the plasma density; therefore, the torus has azimuthal symmetry with respect to Jupiter's magnetic axis. We also assumed that it is symmetric above and below the magnetic equatorial plane. These assumptions allowed us to use both inbound and outbound passes through the torus to draw isodensity lines (Fig. 4). These contours are not unique, but are highly constrained by the observations.

The spacecraft did not pass through the center of the torus; the peak density can only be guessed. We conclude that (i) the torus extended from 5 R_J to more than 8 R_J; its point of maximum density

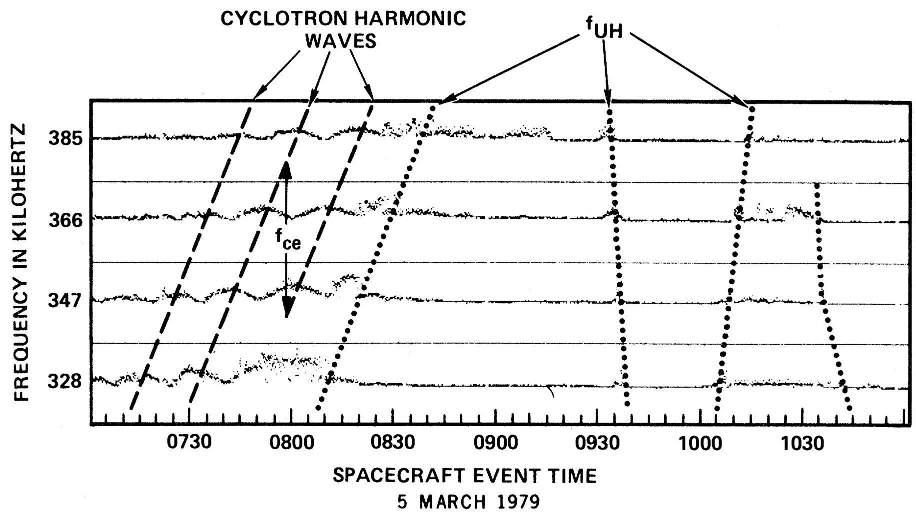

Fig. 3. Example of PRA data on four frequency channels. The smooth oscillations before 0830 are gyro harmonic waves spaced at intervals of f_{ce}. The impulsive emission that follows shows a clear cutoff drifting like a harmonic of f_{ce}. It is assumed to be close to the upper hybrid frequency, which probably follows closely at that time the variations in frequency of the gyrofrequency harmonic. The emissions at f_{uh} around 0935, 1010, and 1140 are sharper and not accompanied by gyro harmonic waves, probably because the variations of upper hybrid and gyro harmonic frequencies differ.

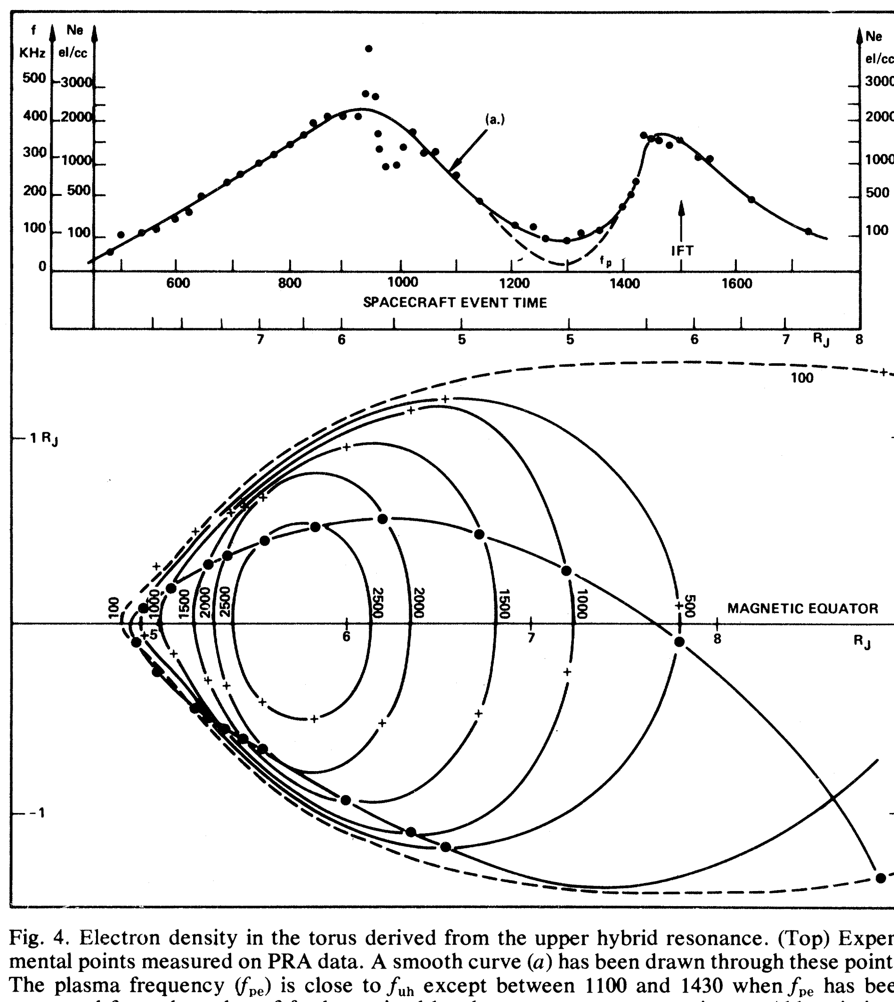

Fig. 4. Electron density in the torus derived from the upper hybrid resonance. (Top) Experimental points measured on PRA data. A smooth curve (*a*) has been drawn through these points. The plasma frequency (f_{pe}) is close to f_{uh} except between 1100 and 1430 when f_{pe} has been computed from the value of f_{ce} determined by the magnetometer experiment. Abbreviations: *IFT*, Io flux tube crossing; *NE*, electrons per cubic centimeter. (Bottom) Isodensity curves in the torus derived from curve *a* under the assumption of an azimuthal symmetry with respect to Jupiter's magnetic axis and symmetry with respect to the magnetic equator. (•) Density points along the spacecraft trajectory; (+) mirror image of the density points with respect to the magnetic equator.

was close to Io's orbit, probably in the range 5.7 to 5.9 R_J; (ii) the maximum value of the electron density in the torus during the flyby was not less than 4500 cm^{-3}; (iii) the density gradient in the equatorial plane was larger inward than outward; and (iv) the bulge in the isodensity curve near 5 R_J was real.

In summary, the PRA experiment detected a plasma torus with high electron density in the magnetic equator at the distance of Io's orbit. The existence of this torus must be taken into account in theories of Jupiter's radio emissions.

Space scarcely allows more than a brief outline of further implications of our encounter data, from which we have introduced here only a small subset. High-frequency cutoffs apparent in decametric emission suggest occultation by the limb of Jupiter of emission from regions beyond the limb. Low-frequency cutoffs in hectometric emission when Voyager was within the plasma torus suggest external reflection of waves below the cutoff frequency. There is clear evidence for Faraday effect in decametric emission propagating through the torus. In a high data rate mode, used for a total of a few minutes each day throughout the encounter period, we have seen millisecond bursts in decametric emissions as well as very short bursts in the hectometric range. We have searched a limited set of these records for evidence of lightning, but the analysis is not yet conclusive. Finally, we have comparisons to make with Voyager 2, still bound for Jupiter and arriving there on 9 July 1979, with Earth-based stations observing Jupiter simultaneously with Voyager 1, and with the complementary experiments on both spacecraft.

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Low-Energy Charged Particle Environment at Jupiter: A First Look

Abstract. *The low-energy charged particle instrument on Voyager was designed to measure the hot plasma (electron and ion energies ⩾ 15 and ⩾ 30 kiloelectron volts, respectively) component of the Jovian magnetosphere. Protons, heavier ions, and electrons at these energies were detected nearly a third of an astronomical unit before encounter with the planet. The hot plasma near the magnetosphere boundary is predominantly composed of protons, oxygen, and sulfur in comparable proportions and a nonthermal power-law tail; its temperature is about 3×10^8 K, density about 5×10^{-3} per cubic centimeter, and energy density comparable to that of the magnetic field. The plasma appears to be corotating throughout the magnetosphere; no hot plasma outflow, as suggested by planetary wind theories, is observed. The main constituents of the energetic particle population (⩾ 200 kiloelectron volts per nucleon) are protons, helium, oxygen, sulfur, and some sodium observed throughout the outer magnetosphere; it is probable that the sulfur, sodium, and possibly oxygen originate at Io. Fluxes in the outbound trajectory appear to be enhanced from ~ 90° to ~ 130° longitude (System III). Consistent low-energy particle flux periodicities were not observed on the inbound trajectory; both 5- and 10-hour periodicities were observed on the outbound trajectory. Partial absorption of > 10 million electron volts electrons is observed in the vicinity of the Io flux tube.*

We report preliminary results from measurements obtained with the low-energy charged particle (LECP) instrument on board the Voyager 1 spacecraft during its traversal of the Jovian magnetosphere. The primary objectives of the LECP investigation were to make measurements at low energies (⩾ 15 keV and ⩾ 30 keV for electrons and ions, respectively), to characterize the composition of the particle population, to determine the particle anisotropies, and to search for particle effects associated with Io and its flux tube. The instrument consists of two basic sensors, the low-energy particle telescope (LEPT) and the low-energy magnetospheric particle analyzer (LEMPA), designed to provide measurements in the outer and inner magnetosphere, respectively. The LEPT is primarily a composition instrument capable of identifying the major ion species, while LEMPA performs basic ion-electron measurements at low and high energies with good particle separation over a large (~ 1 to 10^{11} cm^{-2} sec^{-1} sr^{-1}) dynamic range. The overall sensor complement contains 23 solid-state detectors ranging in area from 1.3 mm^2 to 13.8 cm^2 and in thickness from 2.3 μm to 2.4 mm, combined in various configurations. An essential feature is a stepping motor which rotates the sensors in eight steps through 360° in time intervals of either 48 or 192 seconds. A full description of LECP has been given elsewhere (*1*).

Overview. The first indication of the proximity of the Jovian magnetosphere was obtained on 22 January at ~ 600 Jupiter radii, R_J, when sunward-moving ions (> 30 keV) were observed for a brief (about 2 hour) period. The frequency and duration of such occurrences increased as the spacecraft approached Jupiter, culminating in a sustained increase at 180 R_J lasting for approximately 1 day (days 53 to 54) during which sulfur ions were also observed. The anisotropies, composition, and spectra indicate a Jovian origin for these particles.

Figure 1a shows the intensity profiles of selected ion and electron channels during the inbound traversal of the magnetosphere, which began on day 59 with the first bow shock crossing at ~ 85.6 R_J. There were at least five bow shock and magnetopause crossings between 85 and ~ 47 R_J, each of which has obvious signatures in both the electron and ion intensities (Fig. 1a). The diffuse nature of the bow shock boundaries is evident in the energetic ions, particularly for the