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VOYAGER 1 PLANETARY RADIO ASTRONOMY OBSERVATIONS NEAR JUPITER

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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 MHz to about 1 MHz, 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. Many 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 many 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 paper 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-meter 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 MHz to 40.5 MHz (HF) and from 1.2 kHz to 1.3 MHz (LF), respectively. In six seconds the receiver step tunes at intervals of 307.2 kHz and 19.2 kHz through the HF and LF ranges, respectively; the corresponding bandwidths are 200 kHz and 1 kHz. Each step alternates in polarization, from RH to LH, or vice versa. The receiver operated in several other data modes under Voyager computer control, but most of the results reported here utilized the stepping mode.

In the HF 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 right handed 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 Jupiter 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 LF 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).

It is very striking that near closest approach the emissions in all bands changed dramatically in character. 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. Our data are very similar both before and after encounter with essentially no changes in signal levels. This suggests that the radio emissions are not dependent on the solar phase angle within the source regions.

A few months prior to encounter, we began to observe a distinct new radio emission from Jupiter generally in the kilometric band. These emissions 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 frequencies (Fig. 2). The low frequency cutoff between the 59 kHz and 40 kHz channels (Fig. 2) is typical, although emission sometimes extends into our 20 kHz channel. More than half of these storms lie within $\pm$ 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 kilohertz is roughly 10^{10} watts. 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, six seconds. We find 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 R_J. Candidate source locations would have to include auroral regions high over Jupiter's poles, or more probably, the high density plasma torus near the orbit of Io encircling Jupiter. The *in situ* plasma measurements made by PRA during Voyager 1's passage through the torus (discused more fully below) 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 coincidence.

When the spacecraft was between 9 and 5 R_J, near the location where the UVS experiment (3) observed a heavy-ion "torus", 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} = electron gyro frequency). The main support for this interpretation is the observation of similar narrow-band emissions in the Earth's magnetosphere by satellites crossing the plasmapause. The latter emissions are generally very impulsive (4) and are often accompanied by intense emissions at frequencies separated by the electron gyrofrequency. Both kinds of emissions are also clearly visible in the PRA data (Fig. 3).

We show the variation of f_{pe} with time along the spacecraft trajectory on the top 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 of perhaps no more than 20 or 30% 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 clearly 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 ignore these rapid variations and draw an average curve through the experimental points (curve a on Fig. 4). We also assume 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 assume that it is symmetric above and below the magnetic equatorial plane. This allows us to use both inbound and outbound passes through the torus to draw isodensity lines. Fig. 4 shows isodensity curves in a magnetic meridian plane. 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:

(1) The torus extended from 5 R_J to more than 8 R_J; its point of maximum density was close to Io's orbit, probably in the range 5.7 R_J to 5.9 R_J.

(2) The maximum value of the electron density in the torus during the flyby was not less than 4500 cm^{-3}.

(3) The density gradient in the equatorial plane was larger inward than outward.

(4) 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 emission.

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 emissions 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 hectrometric range. We have searched a limited set of these records for evidences of lightning, but the analysis is not yet conclusive. Finally, we have comparisons to make with Voyager 2, still inbound to 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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5. Voyager Magnetometer Experiment - Science, this issue. We thank the members of that team for providing data in advance of publication.

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FIGURE CAPTIONS

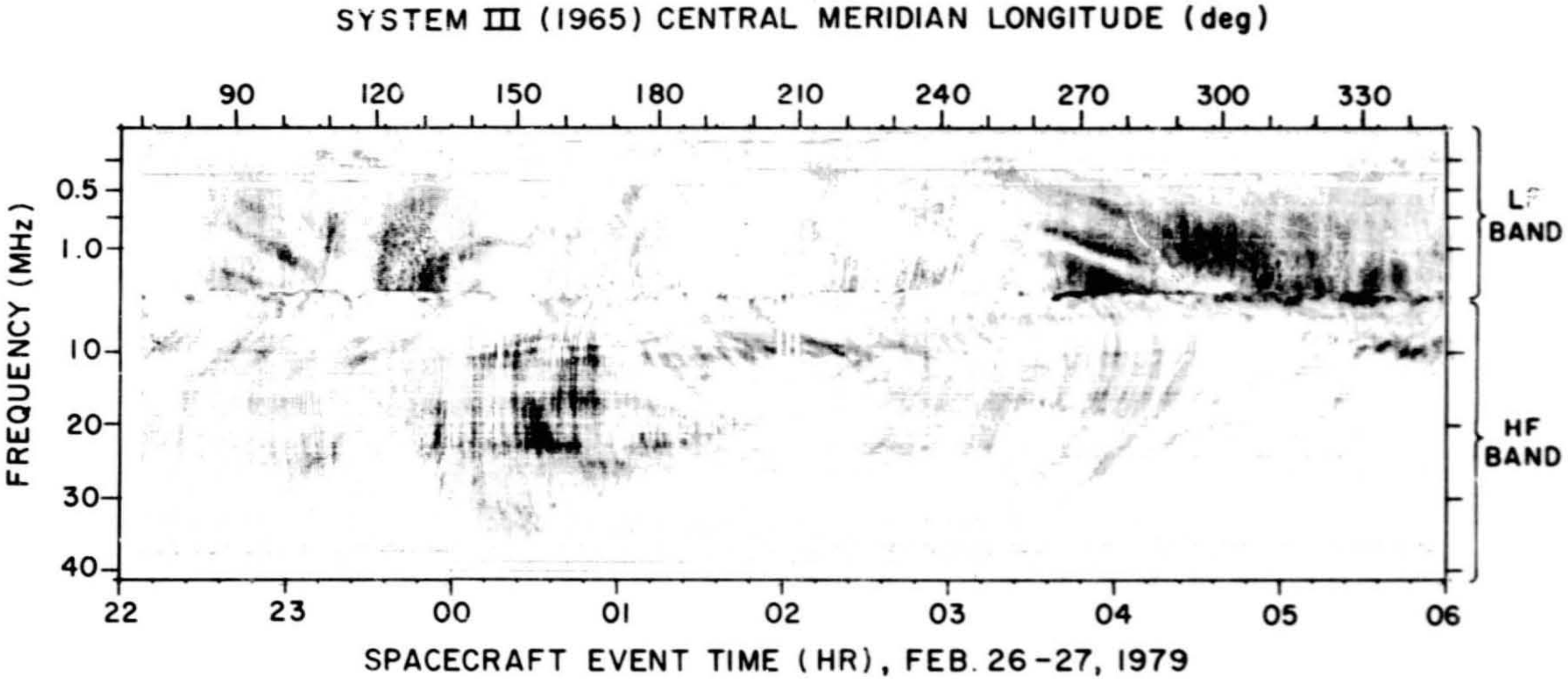
Figure 1. Dynamic spectrum of Jupiter's low frequency radio emissions. The total received power in each of the 198 frequency channels is shown as a function of time and sub-Voyager Jovian longitude. Increasing total power is indicated by increasing darkness. The occasional horizontal streaks are caused by spacecraft-generated interference. During this eight-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 which extend to frequencies as high as 32 MHz near 0400 correspond to the so-called Io-independent emission.

Figure 2. An example of kilometer-wavelength emission from Jupiter. In the four-hour interval shown, we plot intensity vs. time at 15 frequencies between 20 and 462 kHz. Time resolution is six seconds. Kilometric emission is clearly evident at every frequency between 59 and 404 kHz, characteristic of the events we have observed; 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 six 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 another such event is shown in Fig. 1 from 0130 - 0230 between 75 and 250 kHz.

Figure 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 which follows shows a clear cutoff drifting like an harmonic of f_{ce}. It is assumed to be close to the upper hybrid frequency, which likely follows closely at that time the variations in frequency of gyro frequency harmonics. 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 are quite different.

Figure 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 very close to f_{uh} except between 1100 and 1430 when f_{pe} has been computed using the value of f_{ce} determined by the magnetometer experiment. IFT = Io flux tube crossing. Bottom. Isodensity curves in the torus derived from curve (a) assuming an azimuthal symmetry with respect to Jupiter's magnetic axis and symmetry with respect to the magnetic equator. (o) density points along the spacecraft trajectory. (+) mirror image of the o points with respect to the magnetic equator.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90
120
150
180
210
240
270
300
330
FREQUENCY (MHz)
0.5
1.0
10
20
30
40
LF BAND
HF BAND
22
23
00
01
02
03
04
05
06
SPACECRAFT EVENT TIME (HR), FEB. 26-27, 1979

Figure 1

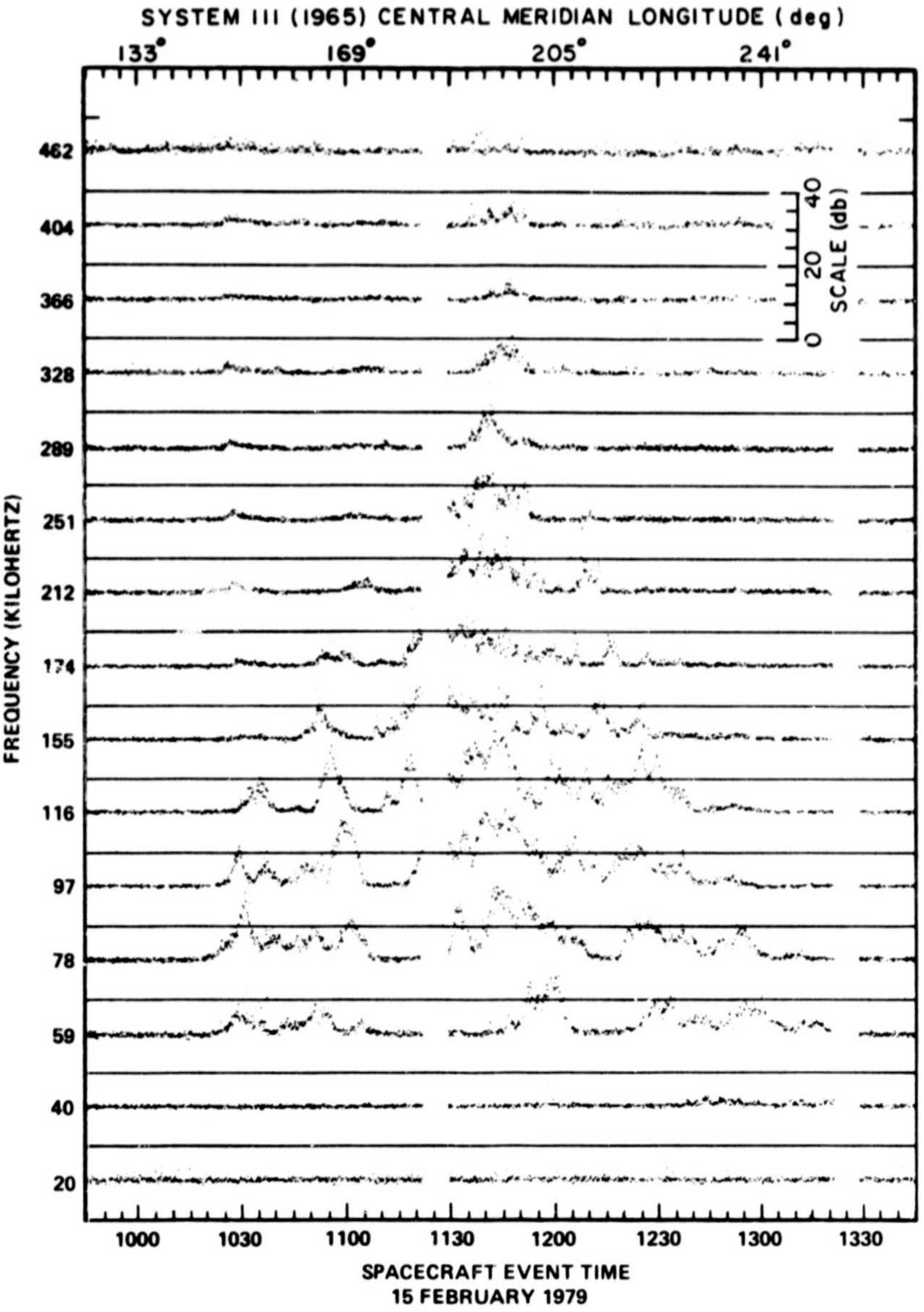

SYSTEM III (1965) CENTRAL MERIDIAN LONGITUDE (deg)
133°
169°
205°
241°
FREQUENCY (KILOHERTZ)
462
404
366
328
289
251
212
174
155
116
97
78
59
40
20
SCALE (db)
0
20
40
1000
1030
1100
1130
1200
1230
1300
1330
SPACECRAFT EVENT TIME
15 FEBRUARY 1979

Figure 2

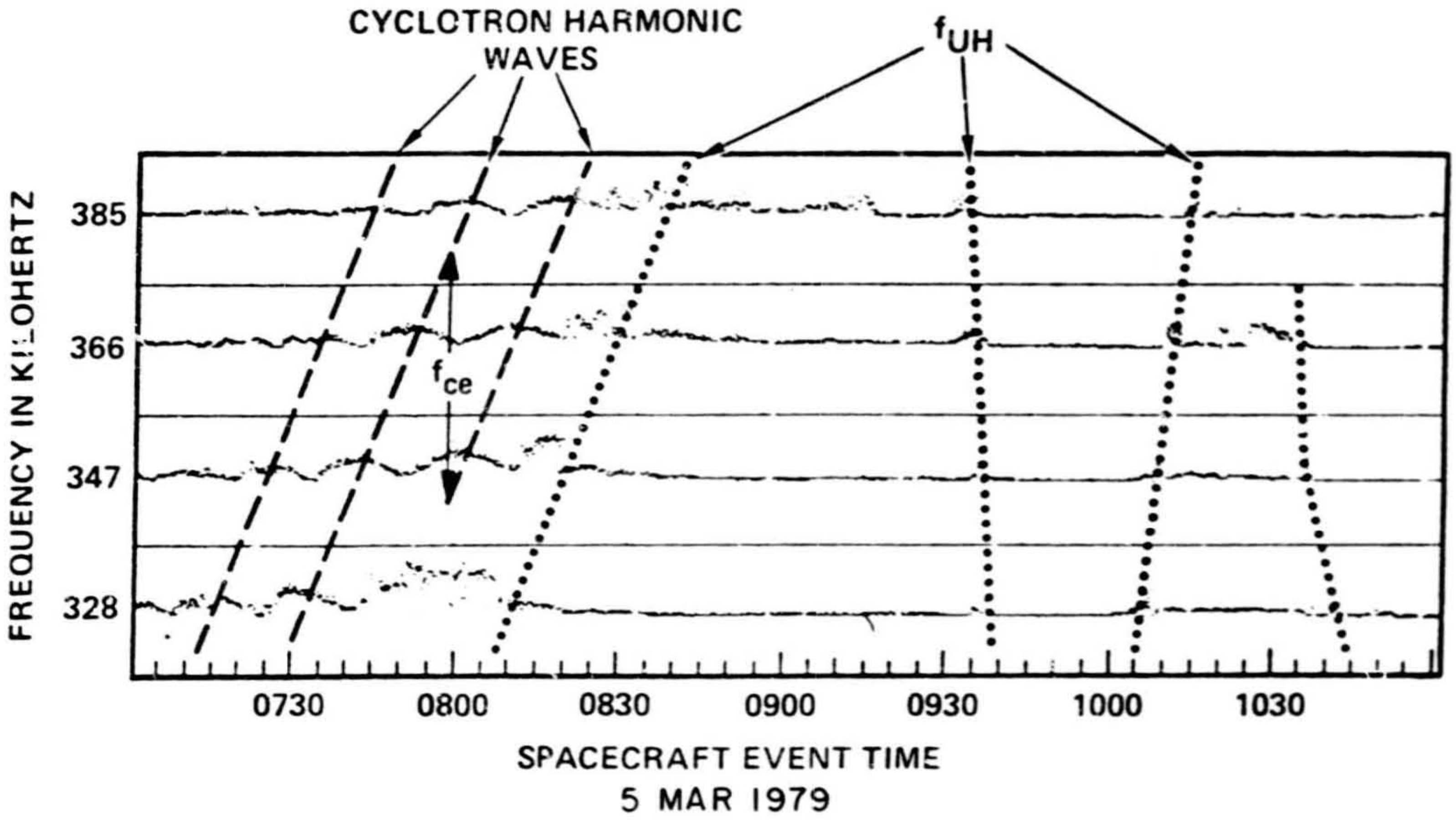
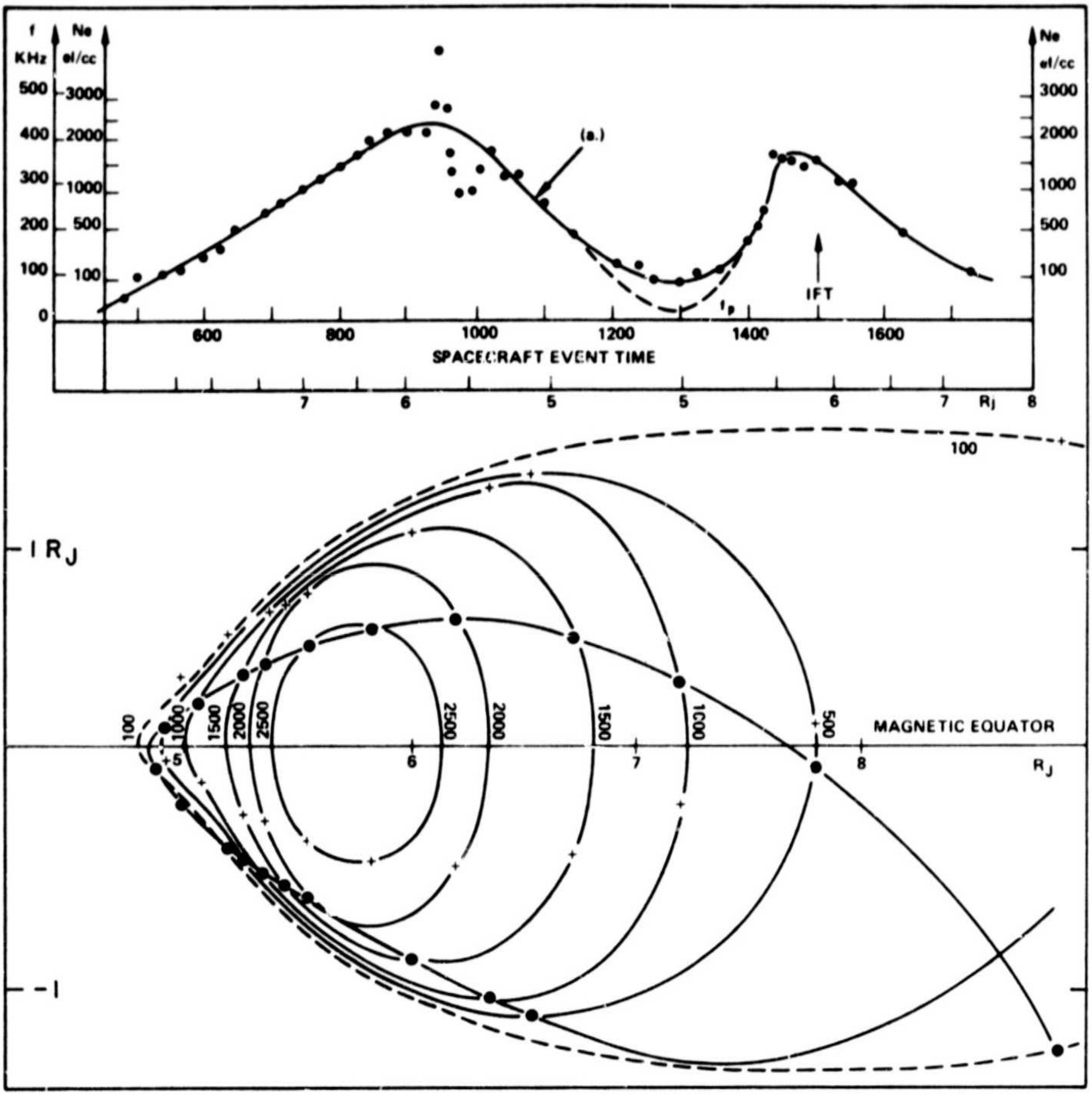

CYCLOTRON HARMONIC WAVES
f_{UH}
f_{ce}
FREQUENCY IN KILOHERTZ
385
366
347
328
0730
0800
0830
0900
0930
1000
1030
SPACECRAFT EVENT TIME
5 MAR 1979

Figure 3



f KHz
Ne el/cc
500
400
300
200
100
0
3000
2000
1000
500
100
(a.)
f_p
IFT
600
800
1000
1200
1400
1600
SPACECRAFT EVENT TIME
7
6
5
5
6
7
R_J
8
100
1 R_J
-1
MAGNETIC EQUATOR
100
1000
1500
2000
2500
2500
2000
1500
1000
500
5
6
7
8
R_J

Figure 4

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