

LOW-FREQUENCY AURORAL RADIO EMISSION FROM JUPITER: THE HECTOMETRIC RADIATION

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Abstract

We review the main characteristics and the inferred properties of the hectometric (HOM) radiation which was observed by IMP-6, RAE-1 and Voyager spacecraft. This includes the occurrence of HOM in Jovian longitude, the strong beaming in latitude, the polarization properties, the local time effect, and the solar wind control of the emission. Like many radio emissions observed at the other magnetized planets, the hectometric component is likely to be generated in the R-X mode from sources in the northern and southern auroral zones. The emission is possibly produced by the cyclotron maser mechanism. We review the HOM in the framework of the other Jovian emissions. Finally, we discuss some outstanding problems still unresolved, but which could be answered when Ulysses will pass around Jupiter.

1 Introduction

Jupiter is the only outer planet which was discovered to emit nonthermal radioemission in the decametric wavelength range [Burke and Franklin, 1955]. The Planetary Radio Astronomy experiment (PRA) on board the Voyager spacecraft [Warwick et al., 1977], observed Jovian emissions from a few kHz to 39.5 MHz. The PRA experiment detected also radio emissions from the Earth, Saturn, Uranus and Neptune. All these planets emit radio emission capable of escaping from the magnetosphere where they are created. Previous reviews on planetary radio emissions were made by Kaiser and Desch [1984] and Boischoat [1988]. More specifically the Jovian radio emission with its very complex radio spectrum has been reviewed after the encounter of Jupiter by Voyager [Carr et al., 1983], and Genova [1987] summarized the results from ground-based observations in the decameter range. In this review we mainly focus on the Jovian radio emission in the hectometric wavelength range, one component which extends from a few tens of kHz to a few MHz.

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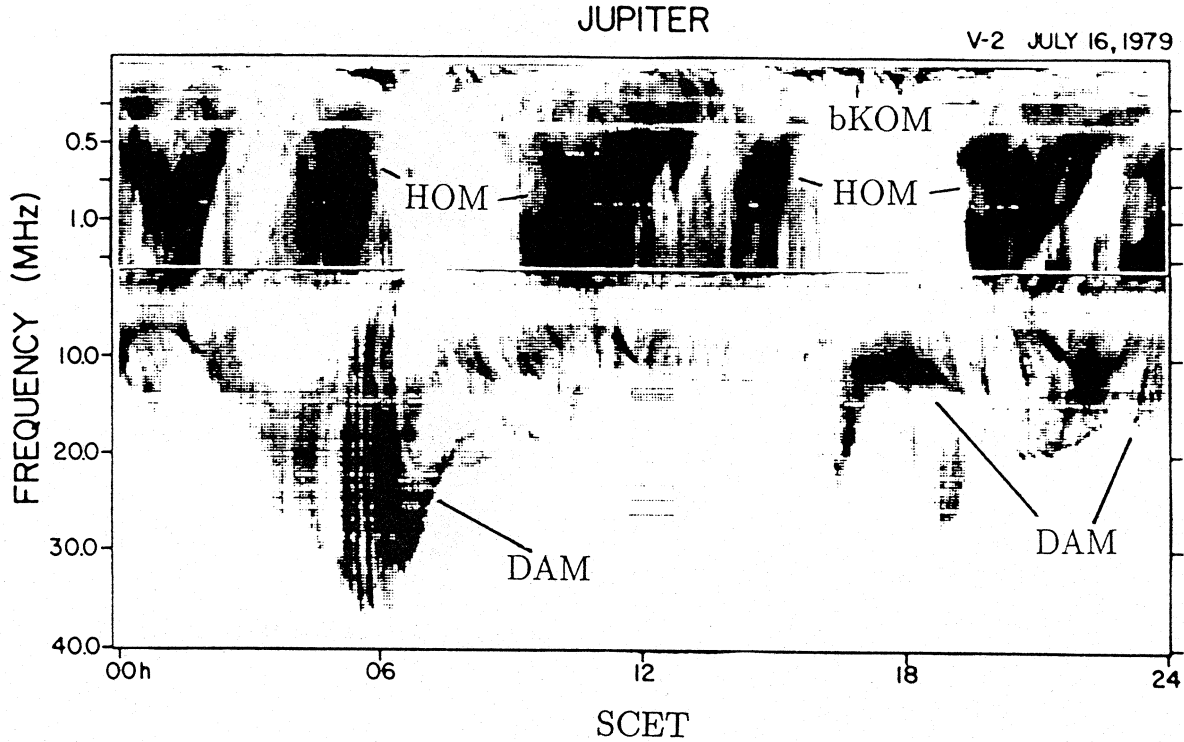


Figure 1: Observations from Voyager 2 planetary radio astronomy experiment one week after closest approach. The observations are displayed in the form of a dynamic spectrum, with increasing darkness proportional to increasing intensity [from Kaiser and Desch, 1984]. We distinguish the DAM, HOM, and bKOM components, as labeled. The near void between about 1.3 MHz (the highest frequency of the low frequency receiver) and about 7 MHz is due to the low sensitivity of the high frequency receiver in that range.

The Voyager 1 and 2 spacecraft encountered Jupiter in 1979 and, as they approached and receded, they provided continuous observations of Jupiter in the hectometric frequency range (HOM) for several years. Earlier, the first low frequency observations of Jovian emissions were taken by the satellites IMP-6 and ISEE-3. A well-defined spectral peak in the hectometric range was discovered [Brown, 1974], leading to the suggestion that it was a distinct component of the Jovian emission. Now, twelve years after the Voyager-Jupiter flybys, a number of results on HOM have been collected by several investigators; we summarize and contrast them in this paper.

The hectometer observations of Voyager 1 (V1) and Voyager 2 (V2) form the basis of most of the studies performed so far. The data were obtained by the PRA experiment whose major emphasis was to study the freely propagating waves generated in planetary plasmas. For a detailed description of this experiment, see Warwick et al. [1977]. Figure 1 is an example of the complex radio spectrum of Jupiter. It was observed one week after the closest approach of Voyager 2. The emission extends from a few tens of kHz to more than 39 MHz, and is repetitive in terms of the Jovian rotation period of 9^h55^m . The radio spectrum of Jupiter consists of various emission components which are called the DAM for Jupiter decameter-wavelength emission, the HOM for Jupiter hectometer-wavelength emission, the KOM for Jupiter kilometer-wavelength emission. At high frequencies ($f > 5$

MHz) we see the DAM emission which has been observed by ground-based observatories since 1955 [Burke and Franklin, 1955]. The DAM is not continuous but appears as a succession of curved, nested arcs, the arc pattern having the form of opening and closing parenthesis [Warwick et al., 1979; Leblanc, 1981; Alexander et al., 1981; Boischot et al., 1981]. The emission controlled by Io, or ‘Io-DAM’ is observed when the Io phase coincides within 30° of two particular values, 90° and 240° [Bigg, 1964]. In the Io-CML plane the Io-DAM has been subdivided into sources called Io-A, Io-B, Io-C and Io-D. In contrast, there is a DAM emission not influenced by the orbital phase of Io, and called ‘non-Io DAM’ [see the review of Carr et al., 1983 and references therein; Kaiser and Desch, 1984; Genova, 1987; Boischot, 1988]. In the range below about 300 kHz lies the kilometric (KOM) emission; it was discovered by the Voyager spacecraft and consists of two components, a broadband (bKOM) emission [Desch and Kaiser, 1980; Leblanc and Daigne, 1985a], and a narrow band (nKOM) emission [Kaiser and Desch, 1980; Daigne and Leblanc, 1986; Jones and Leblanc, 1987 and references therein]. The hectometric emission covers the frequency range from about 40 kHz up to a few MHz, the high frequency limit not being precisely known. From PRA dynamic spectra it cannot be unambiguously distinguished from the DAM, but it is certainly distinct from the kilometric components.

Since its discovery in the late 70ies the HOM was subject of some 30 scientific papers. The different studies of HOM have led to a comprehensive description of the emission. In section 2 we describe some morphological properties of HOM such as the occurrence as a function of central meridian longitude of Jupiter (CML) which can be explained as the result of the beaming of radiation at fixed magnetic latitudes. We further summarize the polarization properties, the local time and external influences; these morphological properties provide the basis for the HOM source model. In section 3 we review the different approaches for the determination of the source location, the beaming pattern and the emission mechanism which is invoked for this radiation. In section 4 we summarize the different results and make some discussions regarding the forthcoming Ulysses observations.

2 HOM phenomenology

2.1 Longitudinal occurrence and beaming in magnetic latitude

Shortly after launch of the Voyager spacecraft in 1977, the PRA receiver detected radio activity from Jupiter in the hectometric range. Figure 2 shows typical HOM observations as collected by Voyagers 1 and 2. The emission occurs nearly at each Jovian rotation [Carr and Wang, 1991], with a characteristic emission gap range around 200° CML. Very stable lane features have also been observed [Alexander et al., 1981]. Alexander et al. [1979] recognized that the range of longitude where HOM is observable depends on the Jovicentric declination (DEC) of the observer. For instance it can be noticed that the emission gap near 200° CML is broader for V2 (at DEC= 7°) than for V1 (at DEC= 3°). Alexander et al. [1979] analyzed statistically the V1 and V2 data together with the HOM observations of the IMP-6 and RAE-1 spacecraft. The four spacecraft were at different Jovicentric declinations from 6° to -3° .

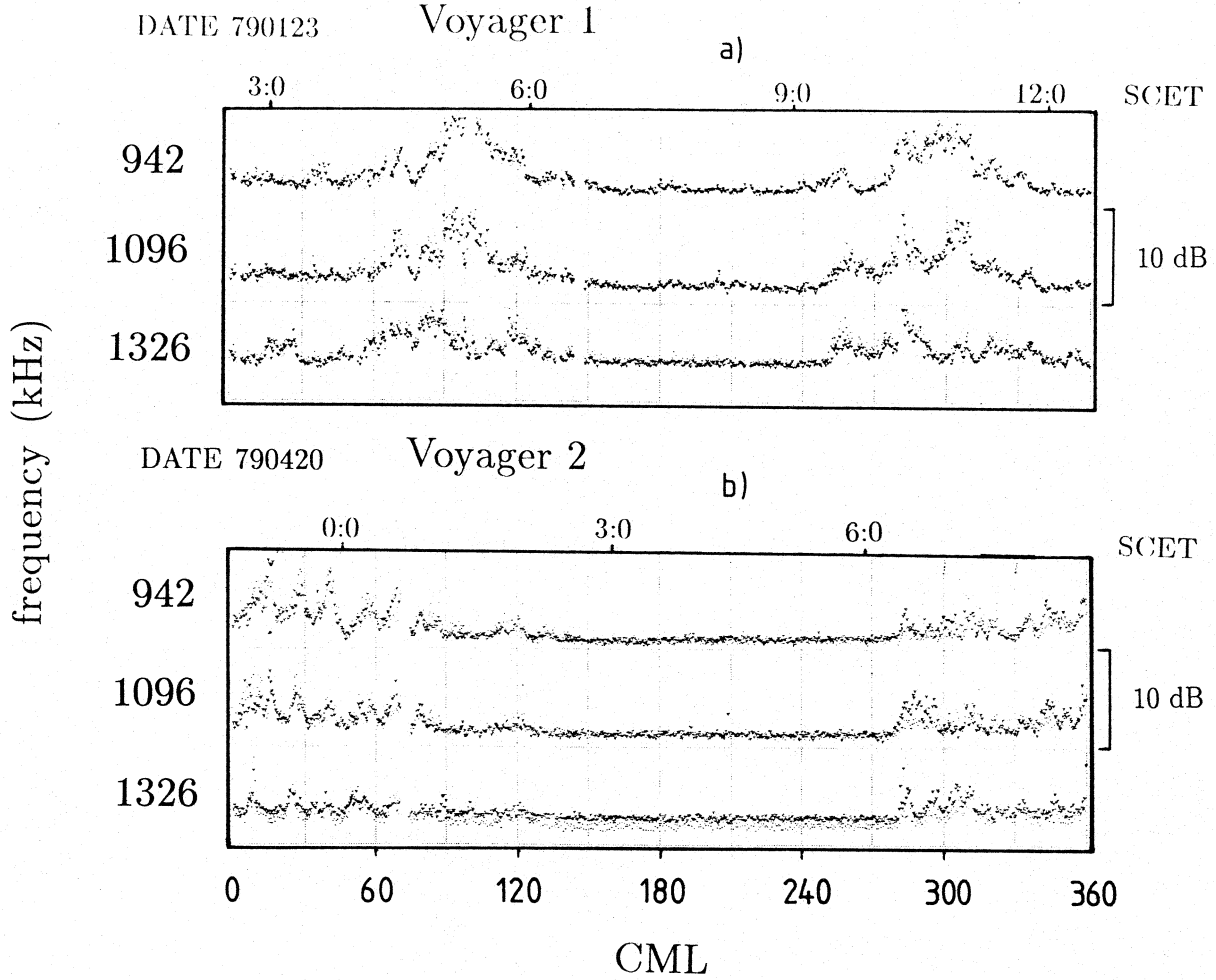


Figure 2: Recorded HOM emission for V1 (top panel) and V2 (bottom panel) during one Jovian rotation before the respective encounters for the 3 indicated frequencies. The emission gap near 200° CML is broader for V2 observations than for V1 observations because of the higher Jovicentric declination of V1 ($DEG=7^\circ$) compared to that of V2 ($DEG=3^\circ$).

A helpful way to interpret the various data sets is to consider the data as a function of magnetic latitude rather than as a function of CML. Figure 3 shows histograms of relative occurrence probability as a function of Jovimagnetic latitude. It can be seen that the hectometric emission pattern can simply be interpreted in terms of a beam, fixed in magnetic latitude, which is centered near the magnetic equator. Since the magnetic dipole axis is tilted by about 10° (toward 200° CML) with respect to the rotation axis, the longitude range where the emission beam crosses the observer will depend on the observer's Jovicentric declination as shown in Figure 2. A statistical estimation of the beamwidth was derived from the data as shown in Figure 3 by Alexander et al. [1979]; they found a beamwidth of 10° centered on 3° magnetic declination. The latitudinal beamwidth has also been studied by Ladreiter and Leblanc [1989] using V1 and V2 observations close to Jupiter. They showed that the beamwidth is a function of the normalized (to a fixed distance) detection threshold, as expected.

Strong latitudinal beaming was also found for the other Jovian radio components. For

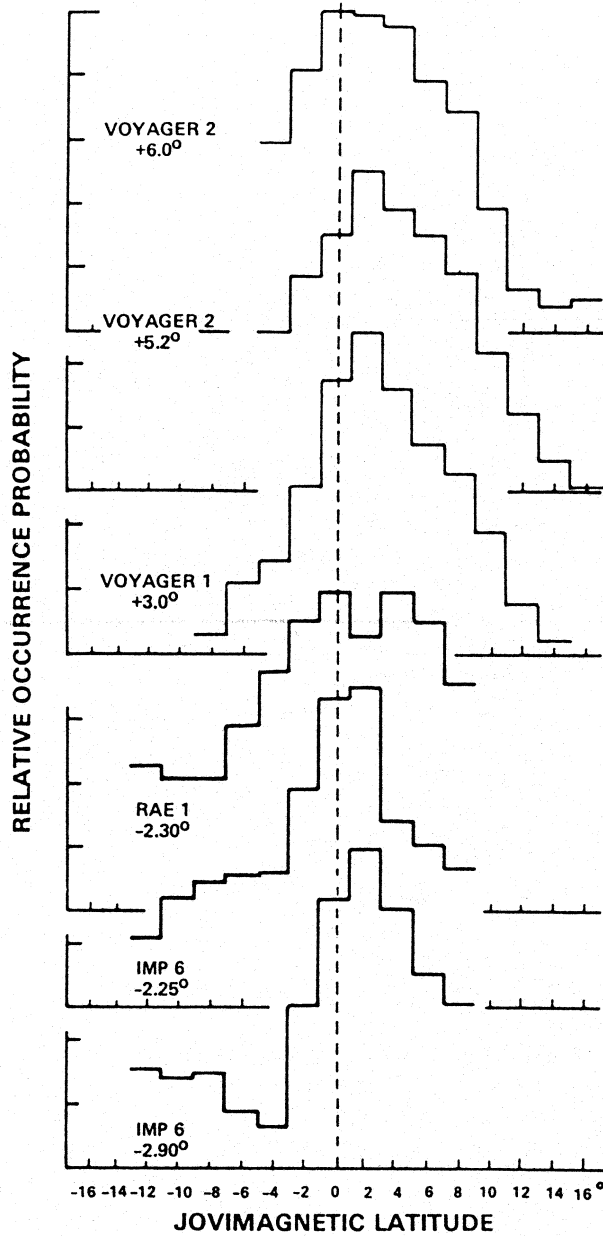


Figure 3: Relative occurrence of Jovian hectometric emission versus spacecraft Jovimagnetic declination for a dipole magnetic field whose north pole is tilted 9.6° towards 202° CML. The data are sorted according to the range of Jovicentric declination of the observing spacecraft for each data set as indicated [from Alexander et al., 1979].

the DAM, Gulkis and Carr [1966] showed that the cyclic drift in longitude of the Io-DAM sources and the variation of their occurrence probability can be explained on the basis of beaming of the escaping radiation, and hence on the Jovicentric declination of the Earth (D_e). The close linear relationship they observed was confirmed by Donovan and Carr [1969], by Bozyan and Douglas [1976], and by Barrow et al. [1982] who used combined spacecraft and ground based observations. The kilometric radiation is also beamed in magnetic latitude. For the broadband (bKOM) component, Leblanc and Daigne [1985a] derived a beamwidth of 3° located from 11° to 14° in magnetic latitude. For the narrow band (nKOM) component, Daigne and Leblanc [1986] found a beamwidth of 12° centered at 7° in magnetic latitude.

The latitudinal beaming is thought to be a consequence of the specific location of the source and its emission pattern. This is also the case for the DAM emission which is

beamed into a hollow conical sheet [Dulk, 1967]. For the HOM, Ladreiter and Leblanc [1990a,b] have shown that the latitudinal beaming is the consequence of the emission pattern (hollow conical sheet) and propagation effects through the Io torus. For the KOM the latitudinal beaming may be the consequence of the emission mechanism itself, as proposed by Jones [1987].

2.2 Polarization

Polarization measurements of HOM as observed by V1 and V2 before and after encounter show a complex behaviour which first was not well understood, and the first reported results were incorrect in some respect [Kaiser et al., 1979; Lecacheux et al., 1980; Alexander et al., 1981; Boischot et al., 1981; Carr et al., 1983]. This was due to the fact that the orientation of the electric plane of the Voyager antenna was not known until Leblanc and Daigne [1985a,b] analyzed the orientation of the electric plane by studying reversals of the bKOM emission. Indeed, Ortega-Molina and Daigne [1984] showed in a comprehensive theoretical study that the antenna physical plane of the PRA system does not coincide with the antenna electric plane at frequencies below 7 MHz. The results of these studies is that the interpretation of the V1 and V2 polarization measurements is straightforward only for a few rotations before the respective Jovian encounters, and somewhat longer after the encounters.

A dynamic spectrum of the polarization state of HOM is shown in Figure 4a. Only the sense of polarization is displayed, not the degree of polarization because Ortega-Molina and Lecacheux [1991] showed that only the predominant sense of polarization can be identified by the PRA receiver. Right-hand circularly polarized (RH) emission is white, left-handed (LH) emission is black, and grey represents equal power in both channels. The sense of polarization has been corrected according to the antenna source geometry. The impression is that RH and LH polarized emission occur in a quite irregular pattern both in time and in frequency. RH emission is generally seen between CML=60° to 330°, with the gap of emission around 200°, it is flanked by LH emission around CML=330° to 360°, and from 0° to 60°.

Ladreiter and Leblanc [1989] performed a statistical study on the HOM polarization. A CML histogram of occurrence of RH and LH emissions as observed by V1 from 790404 to 790413 (a period where clear polarization response was obtained by the PRA) is shown in Figure 4b. This result can be interpreted in terms of two independently radiating sources with left-handed and right-handed emissions, respectively. However, at frequencies below 600 kHz the polarization pattern becomes more complex and sometimes appears to be reversed. The cause of these reversals is not yet understood.

Ortega-Molina and Lecacheux [1991] used the polarization response of the PRA antenna system [Ortega-Molina and Daigne, 1984] to develop a detailed analysis to determine the polarization properties of HOM. The authors explain the HOM polarization pattern by simultaneous radiations from two independent 100 % oppositely polarized sources of slightly different beams and intensities. Both HOM components are circularly polarized as shown in Figure 5 where Ortega-Molina and Lecacheux [1991] analyzed two events during periods of clear PRA polarization response. The Stokes parameter V (degree of

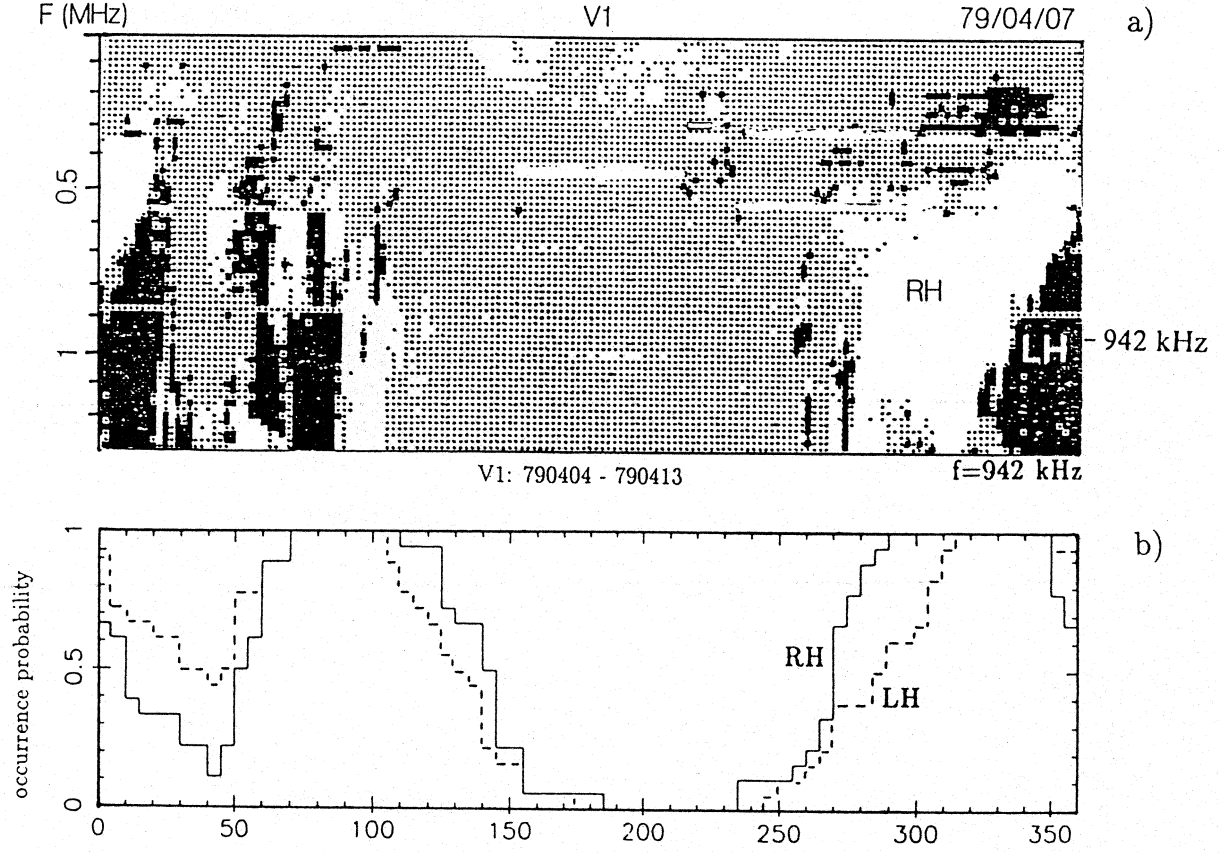


Figure 4: (a) Dynamic spectrum showing the polarization of HOM observed by V1 during one Jovian rotation in the frequency range 20 to 1326 kHz. RH polarization is white and LH is black. (b) CML histogram of occurrence of LH and RH emission as measured by V1 from 790404 to 790413.

circular polarization) peaks at +1 (panel a) and -1 (panel b) thus HOM is likely to be 100% circularly polarized. This is consistent with the idea of right-hand northern and left-hand southern sources emitting in the R-X mode.

2.3 Local time dependence

After the encounter with Jupiter in 1979 both Voyagers were on the nightside of the planet, V1 at 0415 hours in local time (64° from local midnight) and V2 at 0300 hours (45° from local midnight). The comparison of dayside and nightside observations shows a local time effect (variation of the emission morphology as a function of the Sun-Jupiter-spacecraft angle), first reported by Alexander et al. [1981] and by Boischot et al. [1981]. Figure 6 shows CML histograms of normalized flux density at 961 kHz and 1843 kHz for both dayside and nightside observations. It can be seen that the general pattern of shape of occurrence did change from dayside to nightside especially around 20° [Alexander et al., 1981]. Ladreiter and Leblanc [1989] searched for a local time effect on the latitudinal beaming of HOM and found the beamwidth on the nightside to be some 4° narrower than

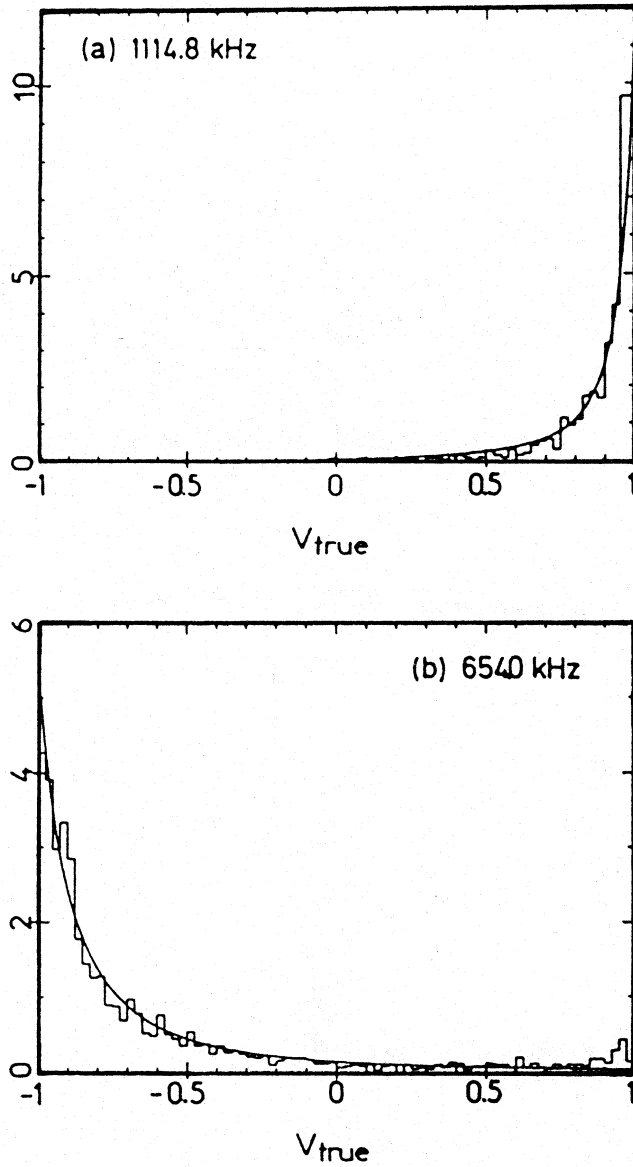


Figure 5: True degree of circular polarization distributions at (a) 1114.8 kHz and (b) 454.0 kHz as observed during March 9 through April 2, 1979. The CML ranges of observation are different, namely in a) $60^\circ - 80^\circ$ and $345^\circ - 15^\circ$ in b). The smooth curves are the best least square fits to the histograms and the peaks are at $V = +1$ (LH circular) and $V = -1$ (RH circular), respectively [from Ortega-Molina and Lecacheux, 1991].

on the dayside. It could not be determined, however, whether this local time effect is intrinsic to the radio source or produced during the HOM propagation in the Io plasma torus. In the latter case it would be the consequence of a difference in the electron density distribution of the Io torus between dayside and nightside.

Local time effects have also been found for the other Jovian emissions, the non-Io DAM and the KOM. Alexander et al. [1981] and Leblanc et al. [1981] showed that when Jupiter was viewed from the dayside hemisphere, the non-Io DAM activity is prevalent at longitudes above 200° , but when viewed from the nightside hemisphere that peak is secondary to the peak at about 160° CML. Leblanc and Daigne [1985a] determined the beamwidths of bKOM and nKOM emissions, and found that they are narrower by a few degrees on the nightside. Since the KOM sources are believed to be located close to the Io torus, it was suggested that the changes from dayside to nightside can be attributed to a difference in the Io torus electron density distribution from dayside to nightside.

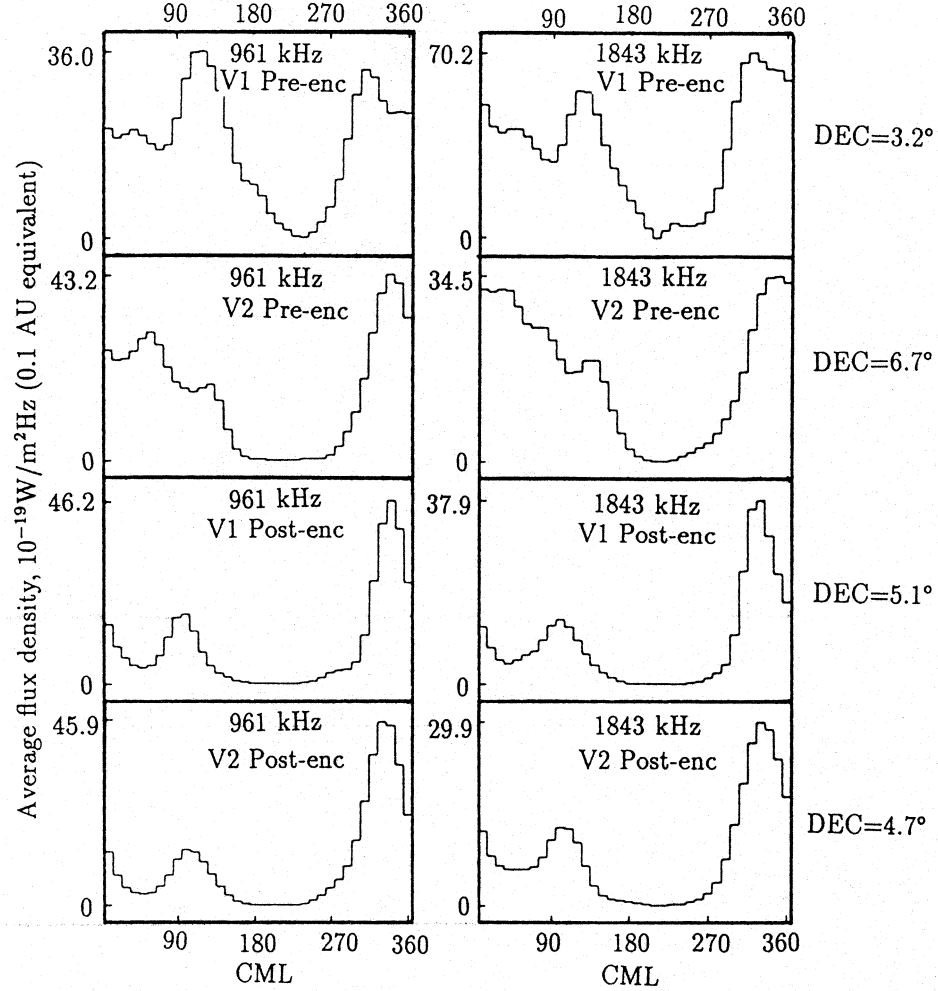


Figure 6: Histograms of HOM average flux density [from Alexander et al., 1981] showing the local time effect on HOM. The change of occurrence probability when comparing pre- and postencounter observations cannot be explained by the variation in Jovicentric latitude of the observer (as indicated in each panel), and must be attributed to a local time effect.

2.4 Relation to DAM and KOM

During the encounters by Voyager 1 and 2, the HOM emission was observed down to about 30–40 kHz [Boischot, 1988; Ladreiter and Leblanc, 1989], but the low frequency limit is usually 200 or 300 kHz. The source extension in altitude, derived by assuming an emission close to the R–X cutoff frequency, is up to 7 Jovian radii, thus the HOM sources cannot be at the Io flux tube at $L=6$. The high frequency limit of HOM is still not known because it is difficult to distinguish HOM from DAM, and because very few homogeneous observations are available in the range 1–10 MHz. This is in part due to the change of sensitivity between the high frequency and low frequency receivers of PRA, the high frequency receiver being less sensitive than the low frequency one. It was very difficult to follow the pattern of the emission from one receiver to the other; in addition many interferences obscured the observations up to 10 MHz. High frequency limits of 3 MHz [Carr et al., 1983] and 7 MHz [Barrow and Desch, 1989] have been suggested. However, it

is not known if the HOM is a distinct component of the DAM as it can be inferred from the observed HOM spectral peak at 1 MHz [Brown, 1974]. Many authors consider HOM just as the low-frequency extension of non-*Io* DAM for the following reasons: (i) Genova et al. [1987] reported that high intensity HOM events are better correlated with non-*Io* DAM emission as observed at Nancay [Leblanc et al., 1981] (ii) solar wind control have been found for both HOM and non-*Io* DAM, although only the latter is correlated with solar wind speed [Barrow and Desch, 1989] (iii) local time dependence have been found for non-*Io* DAM and HOM [Alexander et al., 1981; Leblanc, 1981]; (iv) some features below 2 MHz appear as the extension of arc structures in the DAM [Lecacheux et al., 1980], but between 2 and 20 MHz there is a large gap of observation, and the extrapolation might be confusing.

It is often said that HOM is not controlled by *Io*. However the reported results are not in agreement. According to Desch and Carr [1978] who analysed the Jovian emissions from 1310 to 6550 kHz as observed by the RAE spacecraft, there is some evidence for a slight control by *Io*. They showed that there is an important influence by *Io* over the activity recorded at frequencies as low as 2200 kHz, and even at 1300 kHz. They argue that this control must exist only for high-intensity emissions, in particular at the lower frequencies. Indeed, from ground based observations, by selecting the events of higher intensity, Dulk and Clark [1966] observe a distinct control by *Io* at 8.9 MHz. Alexander et al. [1981] examined the Voyager observations during the period of encounters, from 22 MHz to 400 kHz and found that *Io* affects the flux density of the emission down to below 2 MHz, and there is evidence that the effect continues to as low as 443 kHz. However, Kaiser et al. [1979] did not find evidence of *Io* control in their study of Jupiter activity below 1300 kHz, early in the cruise phase of Voyagers. In conclusion, the relation of HOM with DAM is not still well understood, and it is not yet known whether or not there is some *Io* control on the HOM emission.

The source locations of the Jovian broad-band (bKOM) and narrow-band (nKOM) kilometric emissions are not yet firmly established. While there is some consensus that the nKOM sources are located at the outer flanks of the *Io* torus [Kaiser and Desch, 1980; Jones, 1987], a discrepancy exists concerning the source locations of the bKOM and the emission mode: Whether the sources are at the Jovian auroral zones near the planet or at the *Io* torus near the magnetic equatorial plane, and whether the radiation mode is the O-mode [Green and Gurnett, 1980; Jones, 1987] or the X-mode [Leblanc and Daigne, 1985]. However, no physical relationship is expected to exist between the HOM and KOM since the occurrence in longitude and the polarization properties are distinct.

2.5 Solar wind control

As all of the emissions from the radio planets, the Jovian HOM shows modulation on the time scale of the planetary spin period. Superimposed on, long term fluctuations are always apparent in the HOM observations. These fluctuations were soon attributed to an external origin, in particular to the solar wind activity. In the case of the Earth, it is the solar wind speed that influences the radio emission [Gallagher and d'Angelo, 1981], and for Saturn it is the solar wind density and/or ram pressure [Desch and Rucker, 1983].

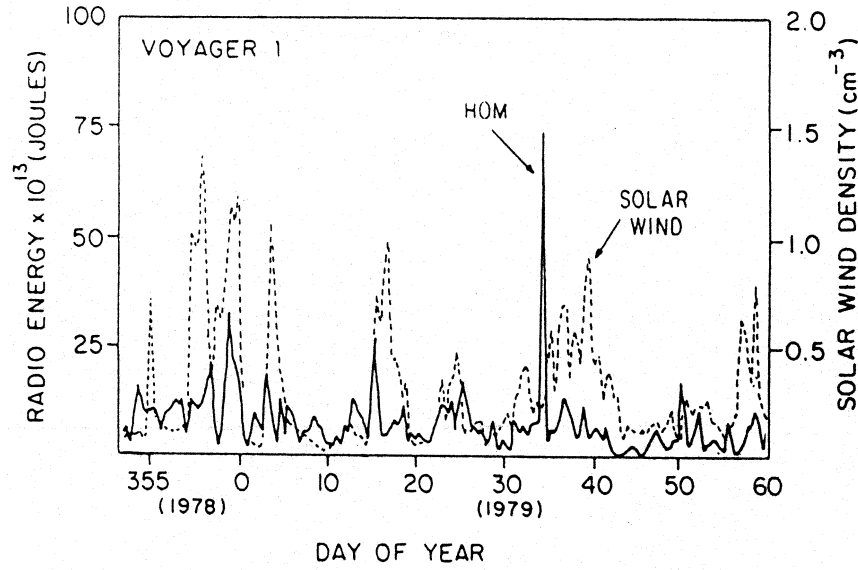


Figure 7: Variation in the HOM energy level compared with the solar wind density for the period December 18, 1978, through March 1, 1979, as observed by Voyager 1. The solar wind profiles are shown as they would appear at Jupiter. Both the solar wind and the HOM data are 10-hour averages [from Desch and Barrow, 1984].

Because Voyager collected HOM data for several years it is possible to study the solar wind influence on HOM. Voyager observations are particularly suitable for such studies since the radio monitoring was continuous over a long time. Moreover, because of the in-situ measurements of the solar wind from the spacecraft, the extrapolation to Jupiter is sufficiently accurate.

All the studies clearly show that HOM energy is correlated with the solar wind density, the ram pressure and the kinetic energy, but not simply with the solar wind speed [Desch and Barrow, 1984; Barrow and Desch, 1989; Rabl et al., 1990]. However the correlation coefficient (solar wind density) is only 0.26 for the V2 data set [Desch and Barrow, 1984]. This value, while significant, shows that the control is not as strong as that of the solar wind control over the terrestrial or Saturnian kilometric radiation. As shown in Figure 7, solar wind density peaks are not always accompanied by strong enhancements of the HOM radio peaks. Nevertheless, there is a significant correlation between HOM energy and solar wind density, and the autocorrelation of solar wind density and HOM energy shows the periodicity of about 13 days (half a solar rotation) which is inherent to the solar wind density periodicity.

Ladreiter and Leblanc [1989] found that increases of the solar wind density are well correlated with the lowest frequencies of HOM (source extending radially outwards) and the largest beamwidths. Consequently strong correlation also exists between those two parameters and the HOM energy: Indeed, the enhancement of HOM energy is consistent with an extension of the source and with a widening of the HOM beam in magnetic latitude.

There is not a general agreement about the influence of the interplanetary magnetic field (IMF) on the HOM energy. Zarka and Genova [1983] studied periodicities in the

HOM emission by a power spectrum analysis. In the power spectra, several peaks were observed, the main ones at $t=29$ days, 14.5 days, and 10.5 days. The authors suggested that these periodicities are associated with the solar rotation period and the passage of the interplanetary magnetic field at Jupiter. Similarly, by using the method of superposed epochs, Barrow and Desch [1989] found that the HOM energy is correlated with the IMF, the correlation being enhanced when the interplanetary magnetic sector structure is well-defined. However, Rabl et al. [1990] by using a linear prediction technique did not find any relationship between the IMF sector transitions and the HOM energy. Indeed, it is very likely that the previous results on the correlation between the IMF and the HOM are due to the interrelation between IMF and the solar wind density.

3 Source localization

In this section we describe the inferred source location of the HOM. Since direction-finding of the incoming radio waves was not possible with the PRA experiment on the Voyager spacecraft, we must use indirect methods to locate the HOM radio sources. The analyses are based on the observations and morphology of HOM as discussed in the previous sections. The techniques utilize the fact that the sources are stable over a long time; as shown by Carr and Wang [1991] HOM is very stable and occurs at every Jovian rotation. In addition the large amount of data collected for several years, and the differing geometry between Jupiter and the spacecraft, put constraints on the source location.

One powerful tool to locate the radio sources is to use ray-tracing calculations [Haselgrove, 1955; Budden, 1961]. It is important to point out that there exists no unique solution for the source regions. The way to limit the possible solutions is to utilize prior knowledge of the generation mechanism and to take into account the beaming characteristics of the emission. For the hectometric emission one must also take into account the presence of the plasma torus at Io's orbit. The in-situ measurements of the plasma density [Birmingham et al., 1981] show that the characteristic frequencies in the torus (plasma frequency, R-X cutoff frequency) are in the hectometric frequency range. Rays are therefore considerably refracted and the hypothesis of straight line propagation is not valid for the HOM.

The first investigation of HOM by ray-tracing was undertaken by Lecacheux [1981], who studied the influence of the Io torus on rays in the HOM frequency range. The Io torus strongly refracts the rays below 1 MHz (Figures 8a,b), and is still important up to 2–3 MHz. Lecacheux [1981] made also calculations from 300 to 2000 kHz to derive the HOM source location. For most frequencies, no source location could be derived, but at 300 kHz he found a possible source location in the southern hemisphere at an altitude where the emitted frequency would be several times the local gyro-frequency.

Recently, Ladreiter and Leblanc [1990a] re-investigated the HOM source location by ray-tracing. They limited the possible source locations by assuming that the generation mechanism is the cyclotron maser instability (CMI) [Wu and Lee, 1979], and by introducing the observed characteristics of the emission. In this context they have assumed that the radiation escapes from the planet in the extraordinary mode within a thin beam along the surfaces of hollow cones whose apexes are distributed at all longitudes in the

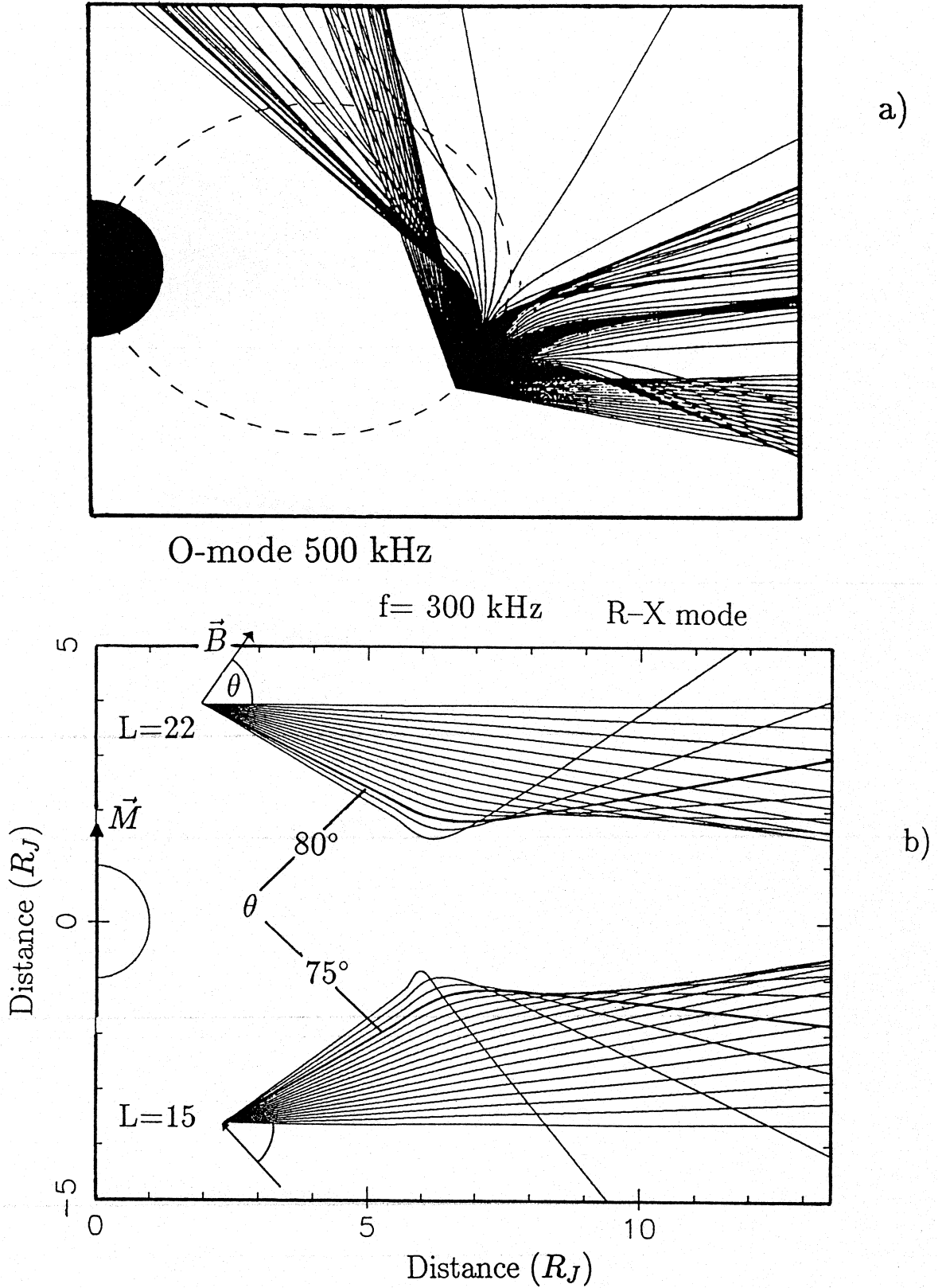


Figure 8: Examples of rays traced in a meridian plane of Jupiter from arbitrary source locations. (a) At $f=500$ kHz in the O-mode from a source near the Io plasma torus $L = 6$ [from Lecacheux, 1981] and (b) at 300 kHz in the X-mode from auroral sources [from Ladreiter and Leblanc, 1990a]. Rays with various wave normal angles θ with respect to the source magnetic field are shown.

northern and southern hemispheres, at altitudes where the gyrofrequency is slightly less than the observed emitted frequency. They searched for sources which produce radiation along the magnetic equatorial plane, in order to produce the observed latitudinal beaming. In a first study rays were traced in the magnetic meridian plane from various possible radio sources to Voyager spacecraft. In the computations, refraction through the Io torus using the model of Divine and Garrett [1983] was taken into account and rays were traced for several frequencies between 40 kHz and 1 MHz. Figure 8b serves as an example of ray-tracing at 300 kHz for rays with various wave normal angles with respect to the magnetic field at the source. The result is that, for a hollow cone with large half angle ($70^\circ < \theta < 90^\circ$), the sources of HOM must be located at $L=15$ to 30 in both hemispheres to be consistent with the Voyager HOM observations near the magnetic equator. As shown in Figure 9, the derived source locations correspond approximately to the innermost field lines that are connected to Jupiter's magnetotail [Connerney et al., 1981], the expected location of the tailfield aurora.

The result just described was based on observations far from Jupiter in the framework of a two-dimensional analysis. A critical test comes from introducing observations made close to the planet. Near the Jovian encounter, the viewing geometry of Voyager with respect to Jupiter changed somewhat, thus some new information could be inferred in the analysis. A further amelioration was the performance of a fully three-dimensional ray-tracing study.

Figures 10a and b show the result of the three-dimensional HOM modeling, typical for the situation at large distances from the planet. Figure 10a shows the HOM beam derived from ray-tracing, at $f=500$ kHz. It is assumed that the emission escapes the source in a hollow cone of half angle $\theta = 75^\circ$ and half power width $\Delta\theta$ of 5° , the sources being distributed over all longitudes. The continuous source distribution in both hemispheres is simulated by 18 subsources, separated by 40° in magnetic longitude. The emission cones which are projected onto a sphere surrounding Jupiter at the actual Voyager distance form the sharp latitudinal HOM beam as has already been postulated by Alexander et al. [1979]. The beam is thus generated by the superposition of many source contributions. Voyager 1 was in the beam when it was near the magnetic equator, and out of the beam when north of it. Figure 10b shows that the modeled intensity profile compares favorably with the observations.

Figures 10c and d represent the situation close to the planet. The modeled cone pattern in Figure 10c predicts a shadow zone near the magnetic equator. This shadow zone is a joint consequence of the refractive effects at the Io torus and the source locations derived above. When the calculated intensity profile is compared to the observations in Figure 10d, the major features are again explained.

In summary this three-dimensional ray-tracing shows that the observed HOM characteristics are well reproduced by sources located at high magnetic latitudes ($L=20$), in both hemispheres, where these sources emit radiation in a hollow cone of half angle $\theta = 75^\circ$, at a frequency close to the gyrofrequency.

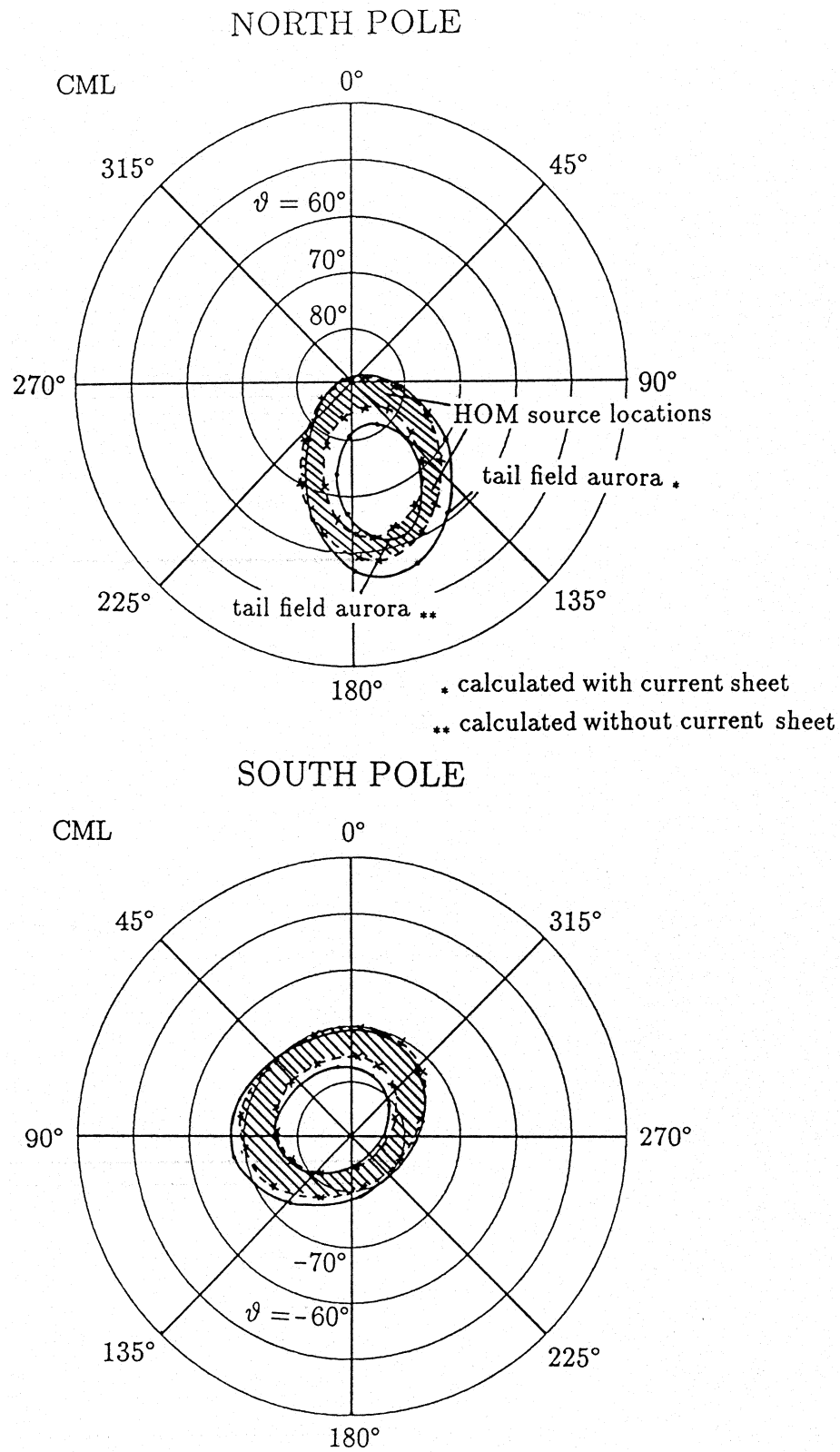


Figure 9: Footprints location of the HOM sources in both hemispheres ($15 < L < 30$). The sources lie along magnetospheric field lines in the tail field aurora [from Ladreiter and Leblanc, 1990a].

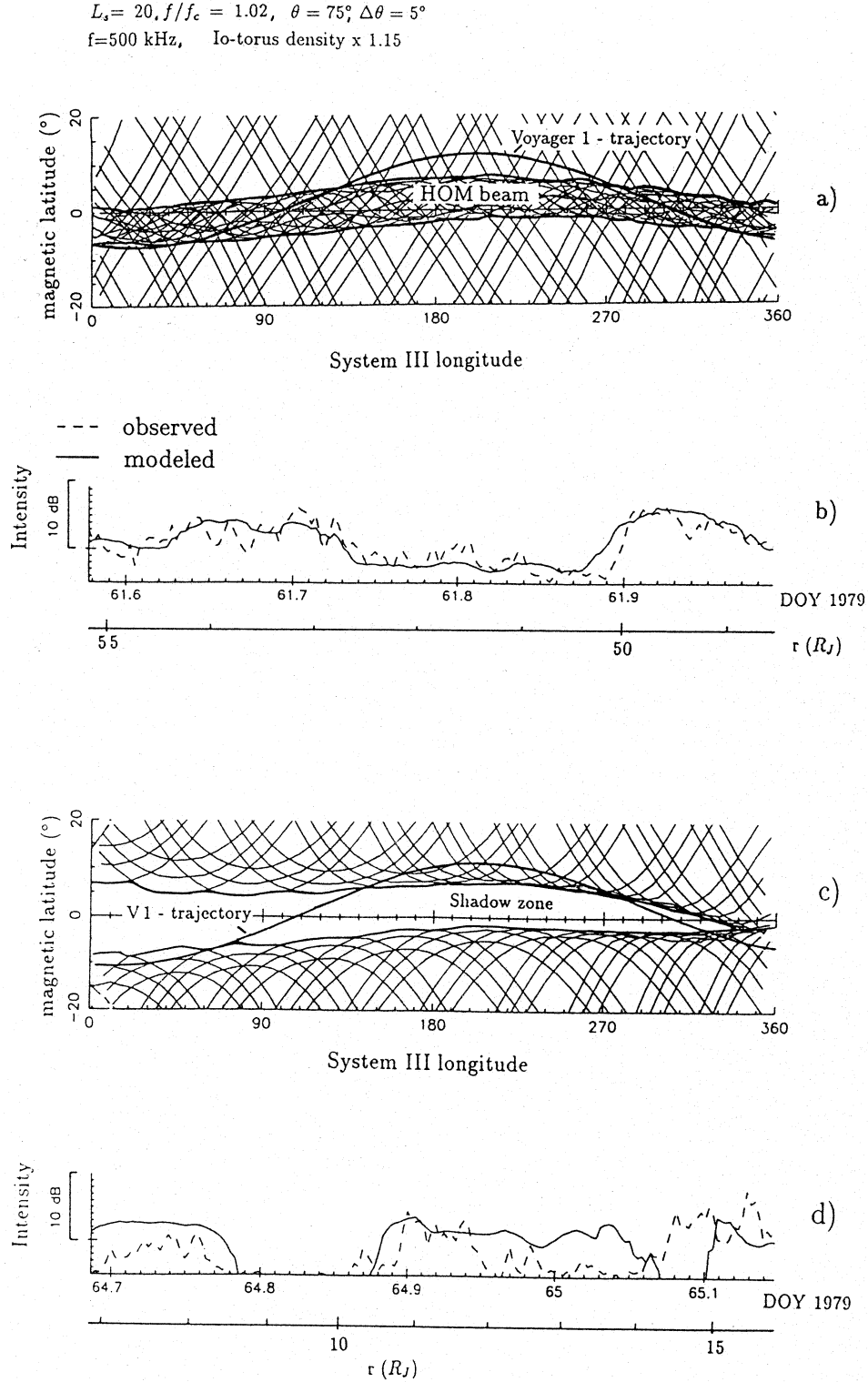


Figure 10: Panels (a) and (b); three-dimensional HOM modeling intensity profile for V1 observations at large distances from Jupiter (see distance scale). (a) HOM emission beam modeled from hollow cone sources with the indicated parameters [see Ladreiter and Leblanc, 1990b for detail], and Voyager 1 trajectory (thick line). The traces of the hollow cones are projected onto a sphere surrounding Jupiter at the actual Voyager distance. (b) The modeled intensity profile compared with the respective V1-PRA observations. (c) Same as panel (a), but for the situation close to Jupiter. The HOM emission cone modeling in (c) shows the existence of a shadow zone which is confirmed by the respective observations in (d).

4 Radiation mechanism

Wu and Lee [1979] developed the theory of the cyclotron maser instability (CMI) for the generation of planetary radio emission. In this theory the radio waves can be generated and amplified by resonance with auroral electrons spiralling along magnetic field lines and having free energy (unstable electrons). The amplification of electromagnetic X-mode waves is generally favoured since the gyromotion of electrons is in the same sense as the E-vector of the fast X-mode.

Le Queau et al. [1984a,b] performed a fully analytical treatment of the CMI. The effect of hot electrons on the dispersion relation was studied by Wong et al. [1982] and Pritchett and Strangeway [1985]. A comprehensive study of the CMI was performed by Pritchett and Winglee [1989] who determined the overall growth rate of the radiation via three dimensional ray-tracing. The CMI theory initially applied to the terrestrial kilometric radiation is now considered to be the mechanism for the auroral emission of the other radio planets .

A study of the CMI in a very low density plasma dominated by the magnetic field ($f_p/f_c < 0.01$) has been performed by Ladreiter [1991], conditions applicable to the HOM sources. He found that the refractive index at the source should be near unity because f/f_c is about 1.01 when the energy of the electrons is 1–10 keV, and then the source region is distinct from the R–X cutoff. In addition, for electrons of energies 1–10 keV, the wave emergent angle at the source is found to be some 80° . It seems therefore that the HOM radiation is also produced by the CMI mechanism. These findings are consistent with those of Galopeau et al. [1989] who analyzed the spectral properties of the Saturnian kilometric radiation, the sources of which are also imbedded in a low density magnetoplasma.

5 Summary and Prospects

Figure 11 summarizes the average observed and inferred properties of the hectometric radiation. Over the years of Voyager observations a wealth of detailed data has been collected. Our interpretations so far concentrate only on the major observed features.

Apart from the summary in Figure 11 the following can be stated:

Frequency range and radiated power: $40 \text{ kHz} < f < \text{a few MHz}$; spectral peak at $\approx 1 \text{ MHz}$ (average flux density [at 4.04 AU] = $5 \cdot 10^{-21} \text{ Wm}^{-2}\text{Hz}^{-1}$).

Relation to other emissions: Possibly the low-frequency extension of non-*Io* DAM. Distinct from KOM.

Source location: High latitude auroral field lines ($L=15\text{--}30$), at heights where $f/f_c \approx 1$ (from $2R_J$ to $7R_J$). Sources distributed over a wide range of longitudes.

Although this list already presents some detailed knowledge about the HOM, some outstanding questions remain:

1. What is the high frequency limit of HOM and the relationship with DAM? What is the lowest frequency where Io still exerts some influence? If HOM and non-Io DAM emanate from the same source, what is the reason for the separate spectral peak near 1 MHz ?
2. What is the origin of the temporal variation of the latitudinal beamwidth? Is it caused by the variation of physical parameters at the source regions, or is it a consequence of a change of density and gradient in the Io torus ?
3. How can we explain some polarization reversals at frequencies less than 500 kHz?
4. Is the local time dependence intrinsic to the radio sources or is it caused by different propagation conditions on day and nightside ?
5. What about the source distribution in longitude ?
6. How to explain some of the fine structures in HOM ?

6 Radio observations on Ulysses

We expect to get an answer to some of these questions in the near future with the observations of the Unified Radio and Plasma wave experiment (URAP) [Stone et al., 1983] on board the Ulysses spacecraft, which will encounter Jupiter in early 1992. The URAP experiment will cover the frequency range from a few Hz up to 1 MHz, thus it is well designed to observe the Jovian radiation in the kilometric and hectometric wavelength ranges; however the highest frequency of observation is too low to cover the whole frequency range of HOM and we will be not able to determine the high frequency limit of HOM. This can possibly be done with the radio observations on Galileo spacecraft where the frequency range is from a few Hz to 5.6 MHz. The location of the radio sources can be determined since Ulysses is a spinning spacecraft, and source locations can be easily made by direction finding provided that the incoming radio waves emanate from a source with small extent. For an extended source the URAP experiment is also able to measure the direction of arrival and the angular size of the source, provided that the brightness distribution of the source is known. The state of polarization of HOM can be completely known since the full set of Stokes parameters of the incoming waves can be determined. The trajectories of Ulysses and Voyagers are compared in Figure 12. Unlike Voyagers which remained close to the magnetic equatorial plane, Ulysses will also explore higher magnetic latitudes, in particular during its outbound trajectory.

Close to the encounter, during the inbound, Jupiter will be explored in a magnetic latitude range from about $+15^\circ$ to $+45^\circ$, and during the outbound from about -20° to -45° .

Figure 11: (color plot, next page) Summary of the properties of the JOVIAN HECTOMETRIC EMISSION.

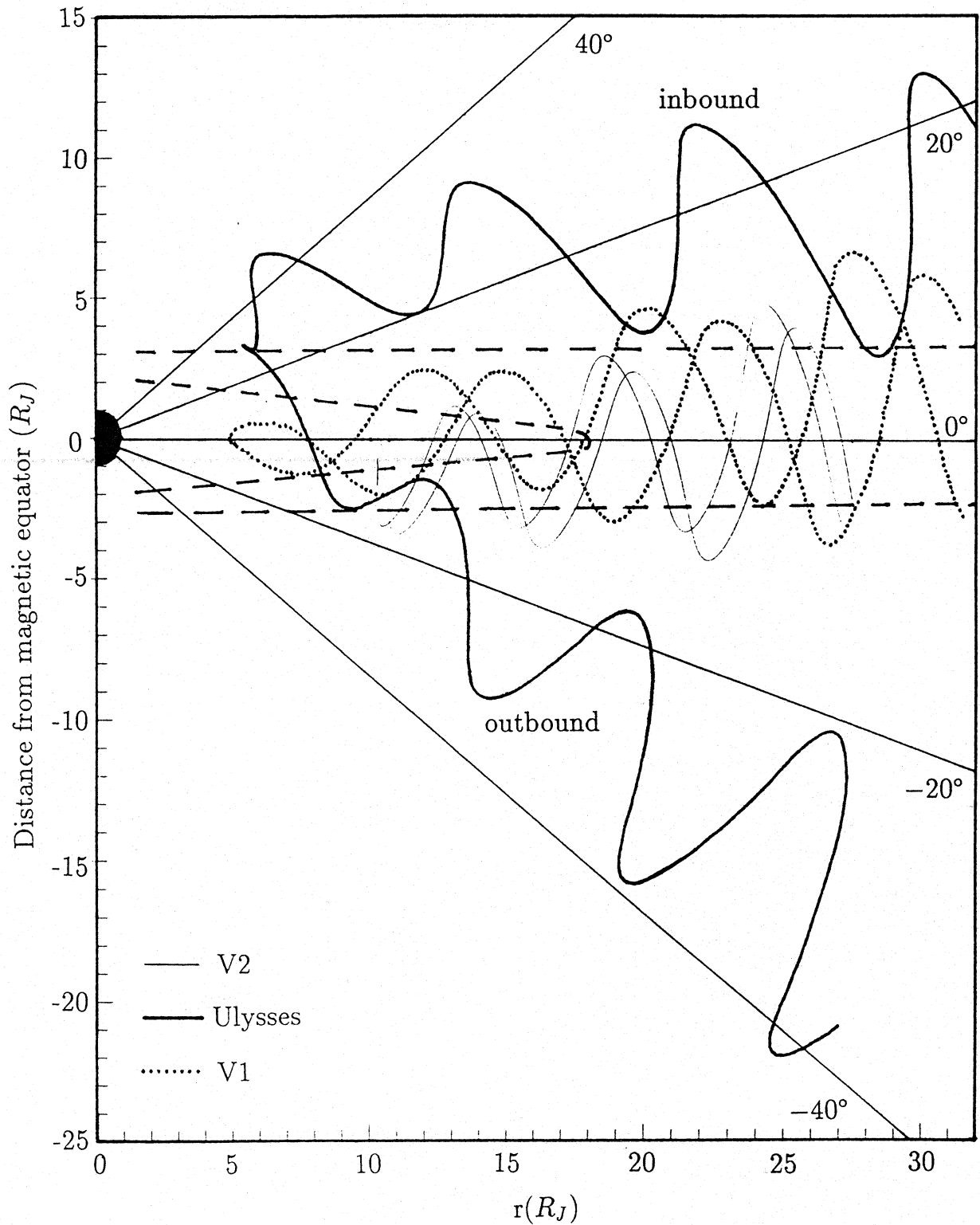


Figure 12: Trajectories of Voyager 1, Voyager 2 and the Ulysses spacecraft in the magnetic meridian plane; the HOM beam is sketched by a dashed line. Ulysses will explore higher magnetic latitudes than Voyager, it will be most of the time outside of the HOM beam, and close to the encounter it will cross the shadow zone of HOM beaming.

Therefore most of the time the spacecraft is expected to be outside of the HOM beam and only weak emission should be observed [Ladreiter and Leblanc, 1991]. But, Ulysses will approach the low-frequency sources in the northern hemisphere, and we expect to determine with more accuracy the low-frequency extension of HOM. Moreover, the emission beam close to the radio source will be observed. Shortly after encounter the spacecraft will cross the Io plasma torus and the HOM shadow zone near the magnetic equator. Ulysses will be in the Jovian southern hemisphere and thus will observe radiation exclusively from the southern source. The peculiar trajectory of the Ulysses spacecraft will provide a lot of new information to explain some of the yet unknown properties of the Jovian hectometric radiation.

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