

POLARIZATION AND BEAMING OF THE JOVIAN bKOM AND HOM OBSERVED AT 5 AU FROM JUPITER BY ULYSSES/URAP

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Abstract

Observations by the Ulysses Unified Radio and Plasma Experiment (URAP), during 1994 and into 1996, have been searched for Jovian broadband (bKOM) and hectometric (HOM) radio emission. Ulysses was then at distances of 5 AU or more from Jupiter and traveling from south to north of the ecliptic plane between jovicentric latitudes -36° to 20° . At these large distances, the events were generally weak and were only received occasionally. Occurrence probabilities and polarization were measured and the characteristics of each emission were compared and found to be quite different.

The HOM was only observed when Ulysses was between jovicentric latitudes -12.2° to 14.7° , quite close to the plane of the jovicentric equator and roughly consistent with previous work based upon Voyager and Ulysses observations made relatively close to each encounter. Both senses of polarization were observed with left-hand (LH) predominant throughout the limited range of jovicentric latitude.

The bKOM was observed at all jovicentric latitudes during the period studied. For the bKOM, however, all but two of the events observed when Ulysses was at northern jovicentric latitudes were predominantly right-hand (RH) polarized while all of the events recorded when the spacecraft was in southerly jovicentric latitudes were predominantly LH polarized, the changeover taking place somewhere between jovicentric latitudes about 4° and 9° , close to 0° *jovimagnetic latitude*. While the HOM results appear to be consistent with an emission process due to the cyclotron maser instability, as suggested by a number of workers in the past, the results for the bKOM present difficulties for the cyclotron maser theory as a possible emission mechanism.

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1 Introduction

The characteristics of the broad-band emission (bKOM) and the hectometre-wave emission (HOM) have been reviewed by Alexander et al. [1981], Boischot et al. [1981], Carr et al. [1983], Kaiser and Desch [1984], Leblanc and Daigne [1985], Boischot [1988] and Leblanc [1988].

Previous work concerning the bKOM and the HOM has been based upon observations made by spacecraft relatively close to encounter. The present paper, however, is concerned with observations made by the Ulysses Unified Radio and Plasma (URAP) experiment [Stone et al., 1992a] when the spacecraft was at distances of the order of 5 AU from Jupiter. In two previous papers, [Barrow et al., 2001a and Barrow et al., 2001b; hitherto called "Paper 1" and "Paper 2," respectively] it was found, in Paper 1, that the bKOM could be observed from all jovicentric latitudes although the polarization of the bKOM appeared to depend upon the jovicentric latitude of Ulysses (D_{Uly}) at the time of the observation. In Paper 2, it was shown that the HOM could only be observed from within a limited range of D_{Uly} although the polarization did not appear to depend upon either D_{Uly} or the jovimagnetic latitude (D_ϕ) of the spacecraft at the time of the observation. The results for the bKOM and the HOM are now compared in the present paper.

2 Ulysses antennas and receivers

The URAP receivers cover two bands, from 1.25 to 48.5 kHz (lo-band) and from 52 to 940 kHz (hi-band). The antenna/receiver system has been described in detail by Stone et al. [1992a] and is summarized in Paper 1. Polarization can only be calculated when the receiver inputs are combined in summation mode (SUM) when the sensitivity is down by about 10 db from separation mode. The procedure is described by Manning and Fainberg [1980].

3 Observations

In Paper 1, URAP observations were searched for bKOM events and, more recently in Paper 2, for HOM events, during the period January 1, 1994, to March 1, 1996, (940101 to 960229, a total of 790 days). During this period, Ulysses was at distances of 4.7 to 7.2 AU from Jupiter and traveling from south to north of the ecliptic plane (see Figure 1 of Paper 1), D_{Uly} changing from about -36° to 20° . While the bKOM presents new problems, the observational features of the HOM at these large distances appear to be roughly consistent with previous work [Alexander et al., 1979; Ladreiter and Leblanc, 1989, 1991; Barrow and Lecacheux, 1995]. Although bKOM was observed from all jovicentric latitudes during the period studied, it was found that the HOM could only be seen when $-12.2^\circ \leq D_{Uly} \leq 14.7^\circ$, relatively close to the jovicentric equatorial plane, corresponding to a range

of jovimagnetic latitudes between -8.5° and 14.2° . Both the bKOM and the HOM were only received occasionally and the identification and selection of events suitable for study was limited by a number of considerations, outlined in Papers 1 and 2. Only events which could be identified with a good degree of certainty and for which polarization data are available have been considered. 57 bKOM events, recorded on 51 days and 58 HOM events, recorded on 37 days, eventually met these criteria.

Event occurrence times were measured from the spectra or from single frequency intensity–time plots. The maximum estimated uncertainty was about ± 5 min. or $\pm 3^\circ$ of CML. System III Central Meridian Longitudes (CML) for Ulysses are taken from the NASA SEDR file and corrected for the light–travel time from Jupiter to the spacecraft.

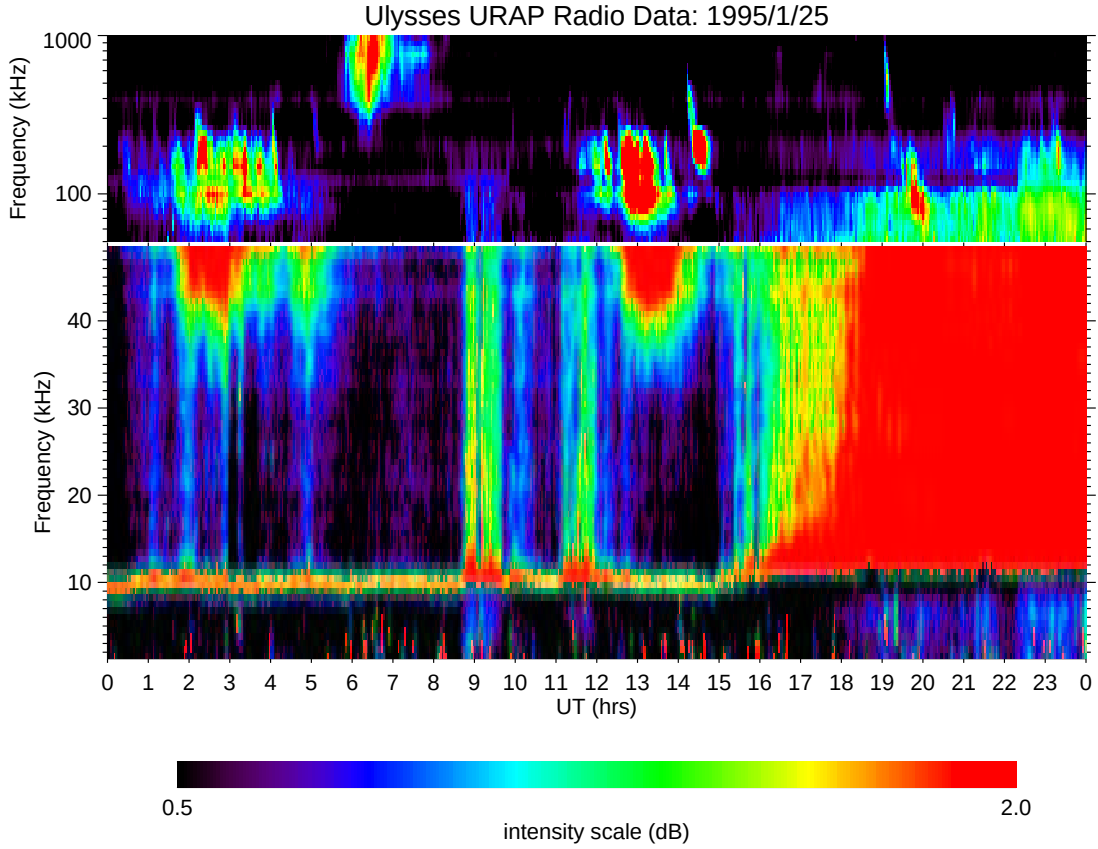


Figure 1: Ulysses/URAP hi- and lo-band spectra for 950125 (DOY 94390)

Typical spectra, taken on 950125 (DOY 94390) when Ulysses was at jovicentric latitude $D_{Uly} = -11.7^\circ$, are shown in Figures 1 and 2 where two bKOM events can be seen to start close to 0200 and 1200 and an HOM event can be seen to start close to 0600. In Figure 1, both the URAP hi-band and lo-band spectra are shown. The HOM is confined to hi-band but the bKOM can be seen in both bands. These spectra were generally used to find and to identify the events. The time resolution of both hi- and lo-band data sets is 144 s. For the lo-band spectrum, three adjacent frequencies are averaged to remove most of the modulation imposed due to the spinning spacecraft–antenna system. Three frequencies are collected in six seconds, which is approximately one-half of the spacecraft

spin period. In hi-band, the data at each frequency are collected for 12 s, approximately equal to the spacecraft spin period; these are averaged together and so spin-modulation should not be present in these data. Much of the typical structure of both the bKOM and the HOM is smoothed out by the effects of temporal broadening due to scattering over the distance traveled by the radiation through the interplanetary medium [Barrow et al., 1999].

The polarization is represented as a spectrum of the degree of circular polarization m_c shown in the second panel of Figure 2. The total intensity $I_L + I_R$ measured by URAP is presented in the top panel. Then m_c , is given by

$$m_c = \frac{I_L - I_R}{I_L + I_R} \quad (1)$$

where I_L and I_R are, respectively, the LH and RH polarized intensities. This could only be calculated when the receiver was in SUM mode and then only for hi-band data [Stone et al., 1992b].

In the third panel, the azimuth, with respect to the direction of the Sun, gave an additional identification criterion and, in particular, distinguished Jovian emission from possible Saturnian (SKR) emission [Lecacheux and Aubier, 1997]. The position of each planet is indicated by the letters "J" or "S" adjacent to the colour scale. The modulation index, shown in the fourth panel, is essentially an indication of the certainty of identification. The numbers above the top panel represent the rotation number of Jupiter, taken as zero on January 1, 1982, and the CML, corrected for light-travel time from Jupiter to Ulysses.

It can be seen that an HOM event began close to 0600 UT (CML $\simeq 156^\circ$). This event was RH polarized (i.e. $m_c < 1$; the emission originated in the northern hemisphere of Jupiter). The bKOM events in Figure 1, can be seen to extend down to some 40 kHz. As polarization data is only available for hi-band, the polarization indicated at the lowest frequencies in hi-band was taken as the polarization for the bKOM event. Thus the event beginning close to 0200 UT (CML $\simeq 156^\circ$) was LH polarized ($m_c > 1$), indicating that the emission originated in the southern hemisphere of Jupiter. There is no polarization data available subsequent to about 0700 UT and so the second period of bKOM emission, close to 1200 UT, could not be included in the analysis. The azimuth spectrum indicates that all of this activity originated from the direction of Jupiter.

Scattering effects in the interplanetary medium [Barrow et al., 1999] will give rise to Faraday rotation in the Jovian emissions. This will tend to depolarize linearly polarized radiation but will only cause phase differences in circularly polarized radiation. Thus the actual sense of polarization will not be changed by scattering [Woan, 1997, 1999].

All of the days when HOM and bKOM events were observed by Ulysses are shown in Figures 3 and 4, respectively. In Figure 3(a) it can be seen that, during the period studied (940101 to 960229), the HOM events were only observed when the spacecraft was in jovicentric latitudes between $-12.2^\circ \leq D_{Uly} \leq 14.7^\circ$, relatively close to the plane of the jovicentric equator. Both senses of polarization were observed with left-hand (LH) predominant. The bKOM events in Figure 4(a), however, were seen from time to time throughout the entire period at all jovicentric latitudes. In all but two cases, LH

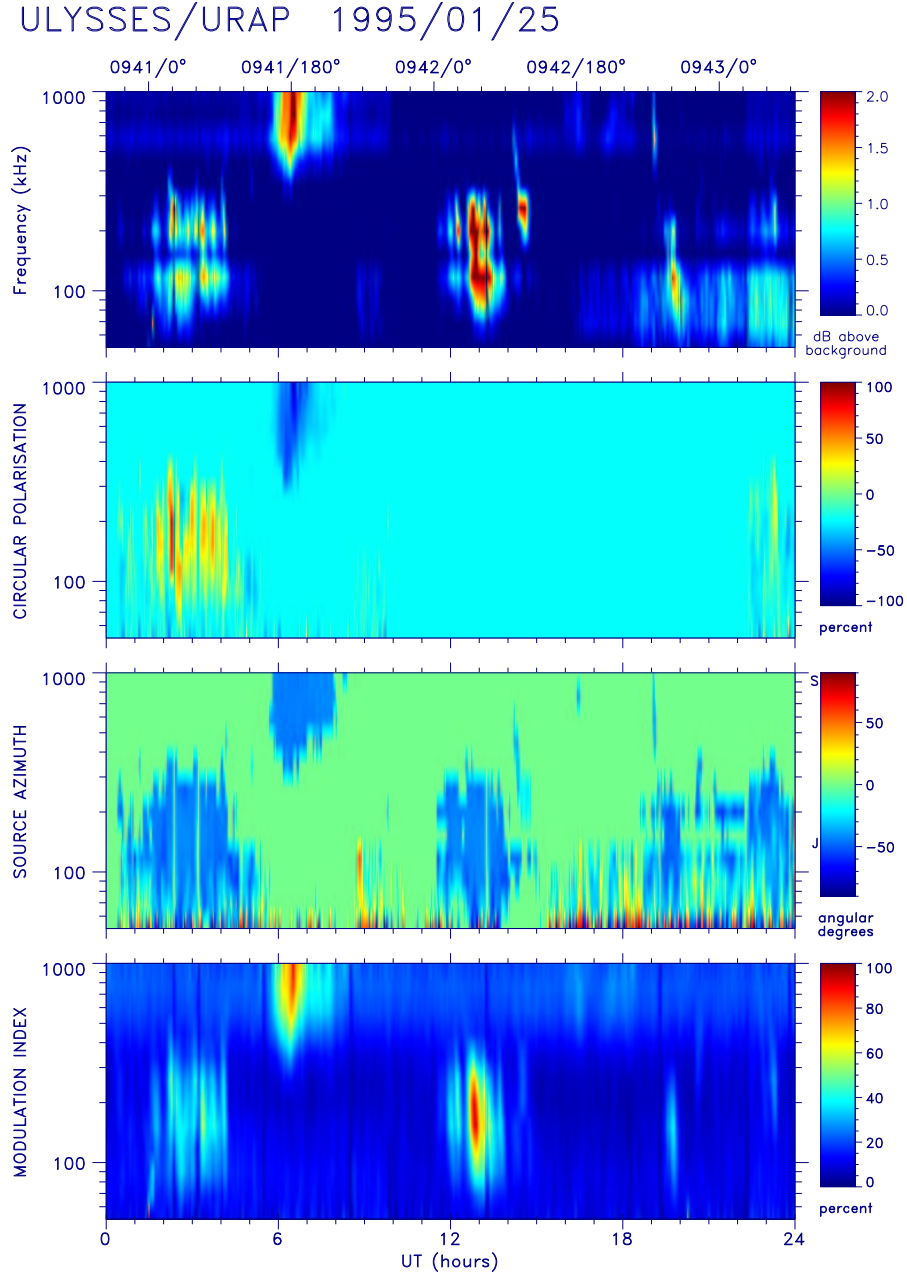


Figure 2: Ulysses/URAP hi-band spectra for 950125 (DOY 94390). The four panels, from top to bottom, show spectra of total intensity, degree of polarization, azimuth of the direction of origin of the emission with respect to the direction of the Sun and modulation index. The numbers along the top of the first spectrum give the Jovian rotation number (zero on 820101) and CML values, corrected for the light-travel time from Jupiter to the spacecraft. The HOM event beginning close to 0600 UT is RH while a bKOM event beginning at about 0100 UT is LH.

polarization was only observed when Ulysses was to the south of the jovicentric equatorial plane and RH polarization only when Ulysses was to the north of the jovicentric equatorial

plane.

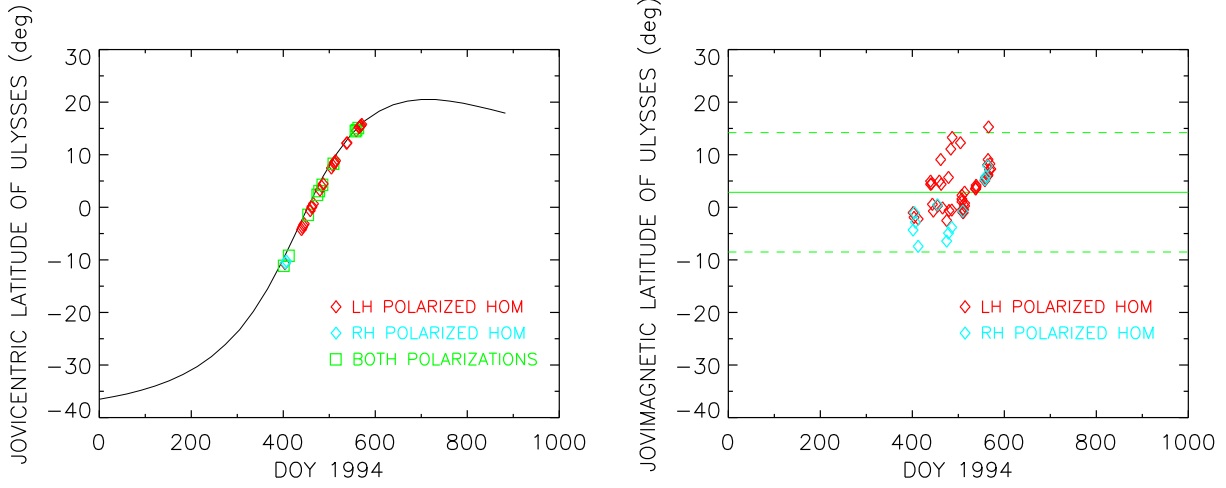


Figure 3: Days on which HOM events were observed by Ulysses, during the period 940101 to 960229 (DOY 94001 to 94790), against (a) jovicentric latitude and (b) jovimagnetic latitude of the spacecraft.

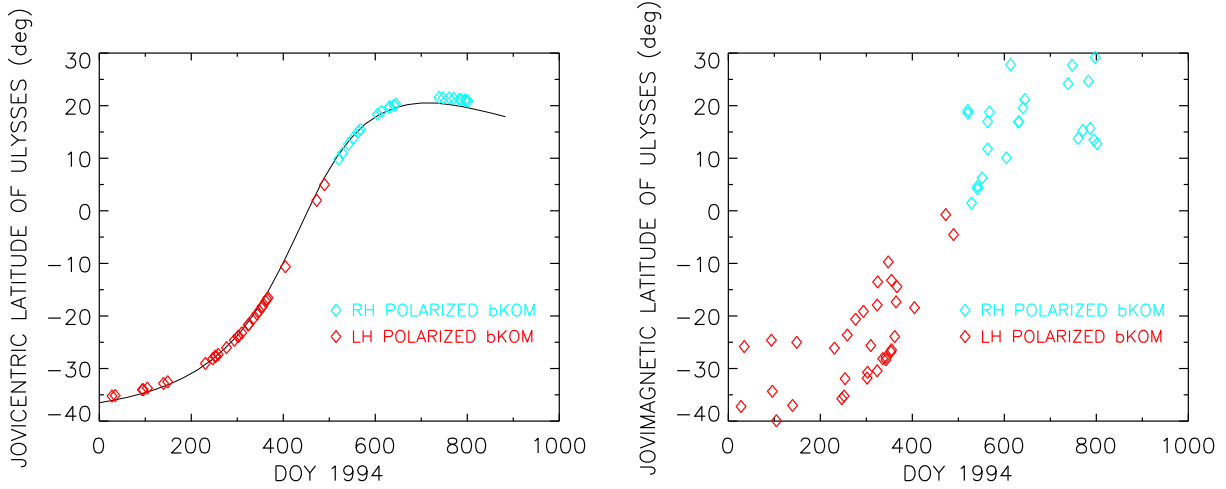


Figure 4: Days on which bKOM events were observed by Ulysses, during the period 940101 to 960229 (DOY 94001 to 94790), against (a) jovicentric latitude and (b) jovimagnetic latitude of the spacecraft.

In Figures 3(b) and 4(b) the same events are plotted against the jovimagnetic latitude of Ulysses at the nearest hour to the event time and these, of course, show a spread of some 20° corresponding to the $\pm 10^\circ$ tilt of the Jovian magnetic field as the planet rotates. In Figure 3(b), of the 12 RH periods of HOM activity, only two occurred without associated LH emission, either immediately before or after the RH emission. It can be seen that all of the events were observed when the spacecraft was within a band of jovimagnetic latitude between -8.5° and 14.2° , centered on about 3° . The central jovimagnetic latitude is the same as that found by Alexander et al. [1979] and by Ladreiter and Leblanc [1989, 1991] but the emission beam is wider. The corresponding plots for the bKOM are shown in Figure 4(b) where it can be seen that this emission was observed at all

jovimagnetic latitudes between about -40° and 30° with a slight decrease of activity close to 0° . Note that all of the RH/LH bKOM events were observed when the spacecraft was in a northerly/southerly jovimagnetic latitude.

Relative occurrence probabilities, for observations of the HOM made when Ulysses was north and south of the jovicentric equatorial plane, are shown in Figures 5(a) and 5(b), respectively. Although the occurrence probabilities are lower, due to the greater distance of the spacecraft from Jupiter, the distributions show some similarity to those found previously by Alexander et al. [1979], shown in Figure 7, for observations made from jovicentric latitudes $-3.2^\circ \leq D_e \leq 6.5^\circ$. For the observations made from northerly (positive) jovicentric latitudes, there is a null centered on about 180° while, for observations made from southerly (negative) jovicentric latitudes there is a single peak centered on about 160° . The occurrence probabilities shown in Figures 5(a) and 5(b) seem to follow this trend and suggest that it continues out to the jovicentric latitudes of Ulysses in the present observations. The pre- and post-encounter Voyager observations studied by Ladreiter and Leblanc [1989] did not include observations made from south of the jovicentric equatorial plane and so they could not show this effect.

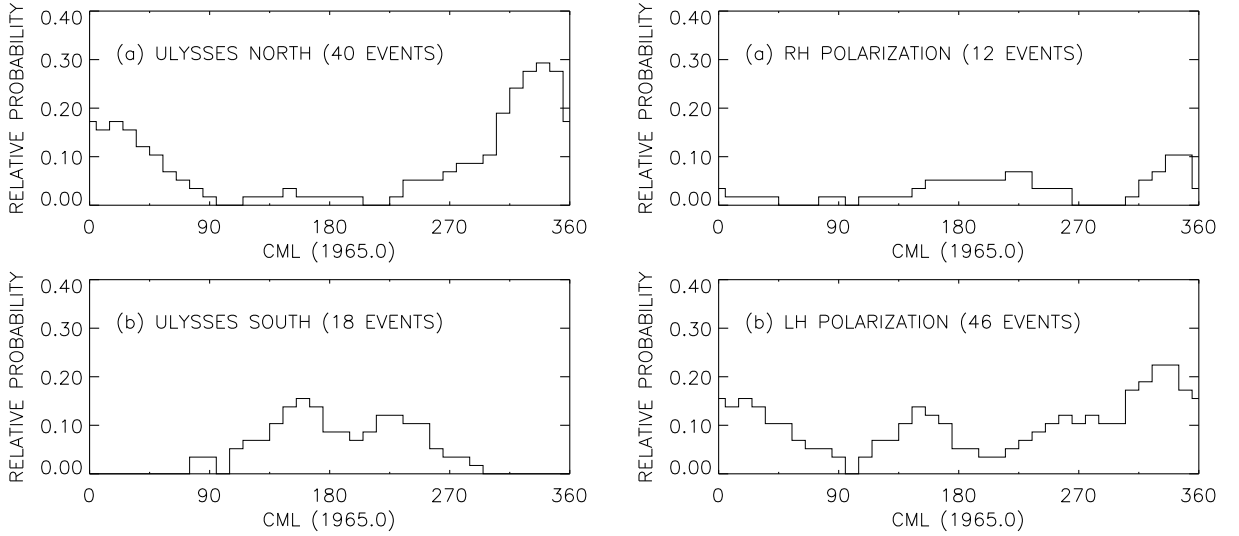


Figure 5: Left: Relative occurrence probability of the HOM observed when the Ulysses was (a) north of the jovicentric equatorial plane, (b) south of the jovicentric equatorial plane.

Figure 6: Right: Relative occurrence probability of the HOM observed by Ulysses for (a) RH polarization and (b) LH polarization.

Occurrence probabilities, for RH and LH polarized HOM, are shown in Figures 6(a) and 6(b), respectively. It can be seen that these occurrence probabilities for the HOM are quite differently distributed from those in Figure 5 while, for the bKOM (Figure 8), it is evident from Figure 4(a) that the distributions north and south are, the same, respectively, as those for RH and LH polarization shown here.

Although the occurrence probabilities here are lower, the LH polarized distribution is essentially the same as that found previously at 52 kHz by Barrow and Lecacheux [1995]. However, the RH polarized distribution differs in that the so-called main source peak,

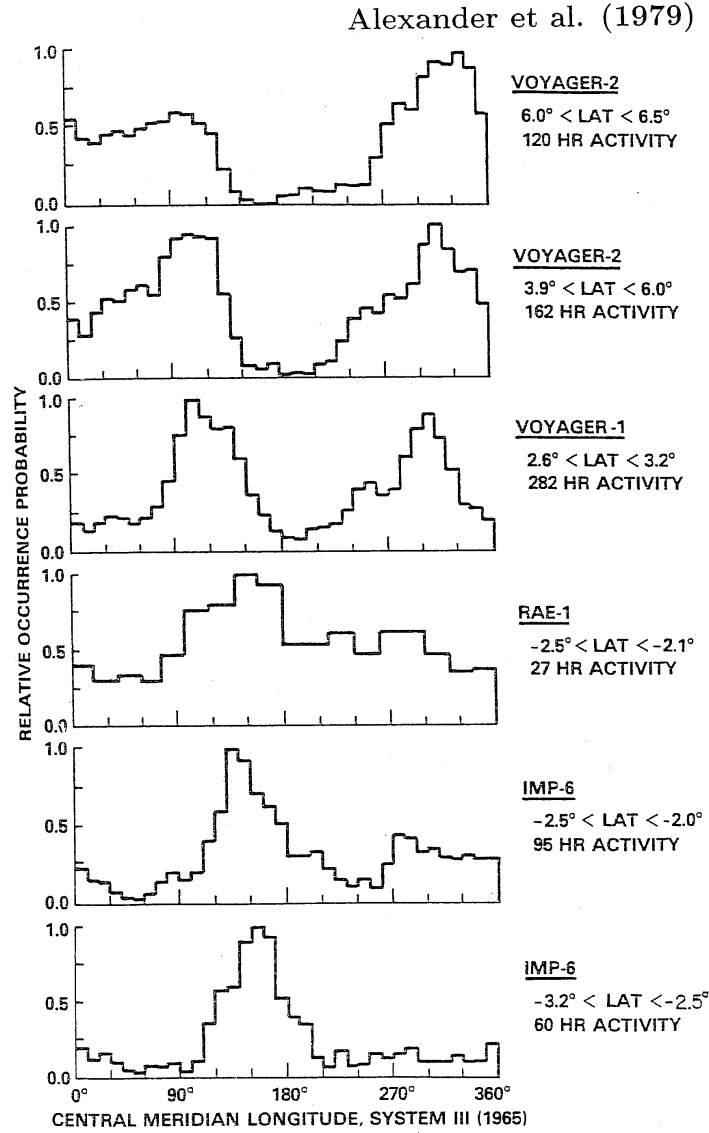


Figure 7: Relative occurrence probability of the HOM for the range of jovicentric latitudes -3.2° to 6.5° [from Alexander et al., 1979].

found in Voyager observations by Leblanc and Daigne [1985], is either absent or, perhaps, displaced towards a larger CML.

Evidently there are a number of differences between the HOM and the bKOM when observed at large distances from Jupiter. These are summarized in Table 1.

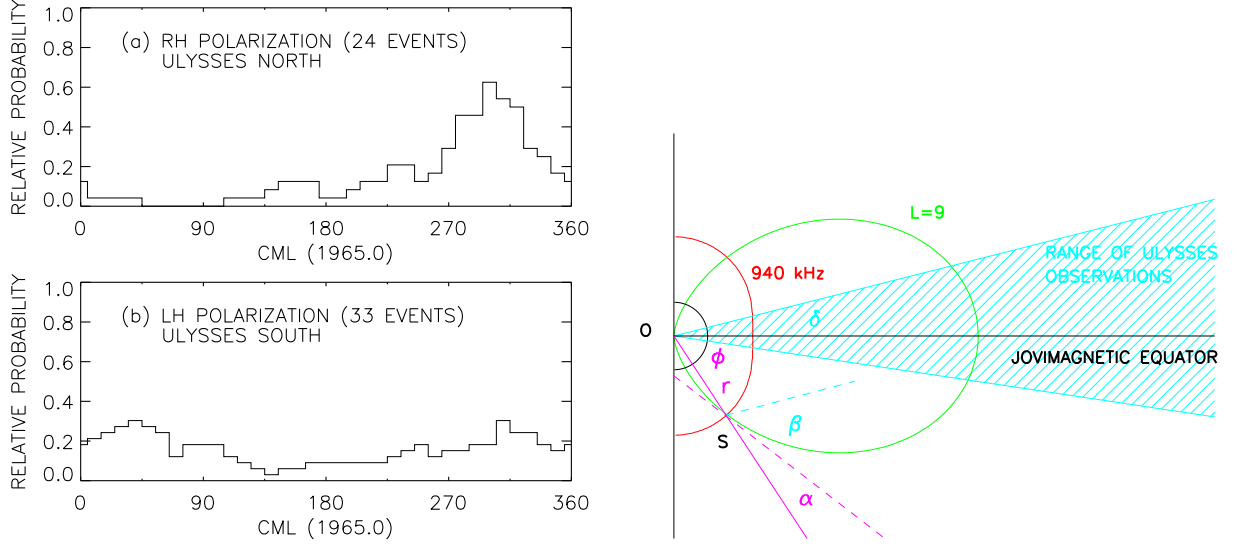


Figure 8: Left: Relative occurrence probability of the bKOM observed (a) when Ulysses was north of the jovicentric equator (RH polarization) and (b) when Ulysses was south of the jovicentric equator (LH polarization).

Figure 9: Right: Two dimensional beaming geometry for HOM emission in a dipole magnetic field from a source on L -shell $\simeq 9$ close to the $f_c = 940$ kHz surface. The shaded area represents the emission beam of the HOM within the jovimagnetic latitudes -8.5° and 14.2° where the HOM was observed.

4 Discussion

A number of workers have suggested that the HOM emission process is due to the Cyclotron–Maser instability (CMI) with dominant emission in the R–X mode. See, for example, Ladreiter et al. [1994b] and the references therein. The emission is beamed into a radiation pattern in the form of a wide-angled thin-walled hollow cone with apex at the source and axis tangent to the magnetic field direction. Propagation is in the R–X mode at frequencies equal to or just above the local gyrofrequency f_c . An event is seen as continuous emission due to radiation from the edges of a succession of CMI cones, distributed over a range of CMLs, and rotating with the planet. The CMI has also been considered as a possible emission process for the bKOM [Ladreiter et al., 1994b].

Beaming can be represented by the two-dimensional geometry of the electron cyclotron frequency surface superimposed upon a dipolar Jovian magnetic field, as sketched in Figure 9 for the HOM, where the point S represents the source (i.e. the apex of an emission cone) in the southern magnetic hemisphere and the northern edge of the cone is directed towards the spacecraft when it is in a northerly magnetic latitude. It is shown in Paper 1 that, if S lies on some specific L -shell, then for a given gyrofrequency f_c at S,

$$\beta = \phi - \alpha \pm \delta \quad (2)$$

where δ is the magnetic latitude of the spacecraft, β is the emission cone half-angle, ϕ is the magnitude of the Jovian magnetic latitude of the source S and α is the angle between

Table 1: Comparison of the characteristics of the bKOM and the HOM as observed by Ulysses at distances of 5 AU or more from Jupiter. 940101–960301: $-36^\circ \leq D_{Uly} \leq 20^\circ$. Ulysses–Jupiter distance: 4.7 to 7.2 AU. D_{Uly} is jovicentric latitude of Ulysses, ϕ_{Uly} is jovimagnetic latitude of Ulysses.

Characteristic	bKOM	HOM
No of events	57	58
Visibility	All D_{Uly}	$-12.2^\circ \leq D_{Uly} \leq 14.7^\circ$
	All ϕ_{Uly}	$-8.5^\circ \leq \phi_{Uly} \leq 14.2^\circ$
Emission centred	?	$\phi_{Uly} \simeq 3^\circ$
Beam width	?	$\simeq 22^\circ$
Polarization	LH: $D_{Uly} \leq 8^\circ$ RH: $D_{Uly} \geq 8^\circ$ Changeover $\phi_{Uly} = 0^\circ$	LH and RH: all D_{Uly} LH predominant
2D Cone half-angle	$\beta \leq 25^\circ$	$30^\circ \leq \beta \leq 52^\circ$
Assumptions	$f_c=52$ kHz, L=15	$f_c=940$ kHz, L=9
CMI theory	Difficulties	Consistent

the field line and OS at the point S. The geometry is the same for both hemispheres but, in equation (2), the positive/negative sign of δ refers to the spacecraft on the opposite/same side of the jovimagnetic equator as the source. Similar geometry applies for the bKOM (see Paper 1).

It follows from equation (2) that, in the two-dimensional model, the detection of emission at a given frequency f_c by a spacecraft at a given location specified by δ determines a unique value of β for an assumed value of L and a given field model. This is not true for the three-dimensional model.

As Jupiter rotates, an observer sees the event as emission from a succession of CMI cones distributed over a range of CMLs. As the cone half-angles have, in general, been found by various workers to be large, estimates ranging from 30° to 90° for the HOM and from 40° to 80° for the bKOM [Ladreitner et al., 1994b] and, as Jupiter rotates at a rate of about $36^\circ/\text{hr}$, an event might be expected to last for some two or three hours as seen in observations close to Jupiter.

The durations of most of the HOM and bKOM events considered here and shown in Figures 3 and 4, were relatively short, often less than an hour; less than typical dura-

tions observed closer to the planet [see, for example, Barrow and Lecacheux, 1995; their Figure 3]. On the other hand, occasional events, like those shown in Figure 1, lasted somewhat longer. If the shorter duration events are not merely an effect of distance from the planet, it may be that some of these are due to emission from sectors of the extreme northern or southern edges of the CMI cones when the source is approximately on the Jupiter–Ulysses meridian or else from a few cone edges if the source is turned away from Ulysses.

The HOM source has been found to lie on some L-shell between 7 and 11 [Ladreitner et al., 1994b], between 8 and 10 [Zarka et al., 2001a] and between 4 to 6 by Reiner et al. [1993b]. In the discussion that follows we will assume that the HOM and the bKOM are generated from tilted dipole field lines close to $L = 9$ and close to $L=15$, respectively. In Figure 9, we show the two-dimensional geometry (i.e. when the emission cone is facing Ulysses) of the beaming, taking the source to be on $L = 9$ where this field line cuts the $f_c = 940$ kHz surface. This source will be at a jovimagnetic latitude of about 56° (north or south) and at a distance of some $2.8 R_J$ from the planet. The shaded area represents the limits of observation of the HOM seen by Ulysses, -8.5° to 14.2° . Some of the HOM would have pass through the Io torus to reach Ulysses but, as the maximum electron density in the torus corresponds to a plasma frequency of about 500 kHz, refraction effects in the torus should be small.

Calculated values of β , for the HOM and the bKOM for the events shown in Figures 3 and 4, are plotted against jovicentric latitude in Figures 10 and 11, assuming a two-dimensional model and values of $f_c = 940$ kHz and $L = 9$ for the HOM and $f_c = 52$ kHz and $L = 15$ for the bKOM. LH events and RH events are plotted separately. It is implicit from equation (2), that there can be no unique value for β that does not involve assumed values of L and f_c . For the HOM, the values of β lie between 30° and 52° . We have seen in Figure 3 that, for the HOM, there is no particular range of either jovicentric or jovimagnetic latitudes that is especially favourable to one or other polarization.

For the bKOM it follows from Figures 6 and 7 in Paper 1 that, if the emission process is due to the CMI, for RH polarization to be observed by the spacecraft when it is in a northerly jovimagnetic latitude, the angle β would have to be rather small if the assumption of $9 \leq L \leq 15$ proposed by Ladreitner et al. [1994b] is to be valid. Similar considerations apply to the observation of LH polarization when Ulysses is at a southerly jovimagnetic latitude. This is further demonstrated in Figure 11 where all of the measured values of β are found to be less than about 25° .

However, the two-dimensional geometry shown in Figure 9 and all of the foregoing discussion assumes that the source is radiating from the face of Jupiter directed towards Ulysses. This may not be the case because the locii of the intersections of L and f_c are circles around the planet, one to the north and one to the south of the jovimagnetic equator. In the direction finding analysis presented by Ladreitner et al. [1994b], it is evident that large-angle emission cones must point away from Ulysses, i.e. be close to the limb of the planet with respect to Ulysses, if their edges are to radiate in the direction of the spacecraft. This may well be the case although, for the bKOM, the following questions then arise:

1. If the cone angle is large why was RH polarized bKOM not received after encounter

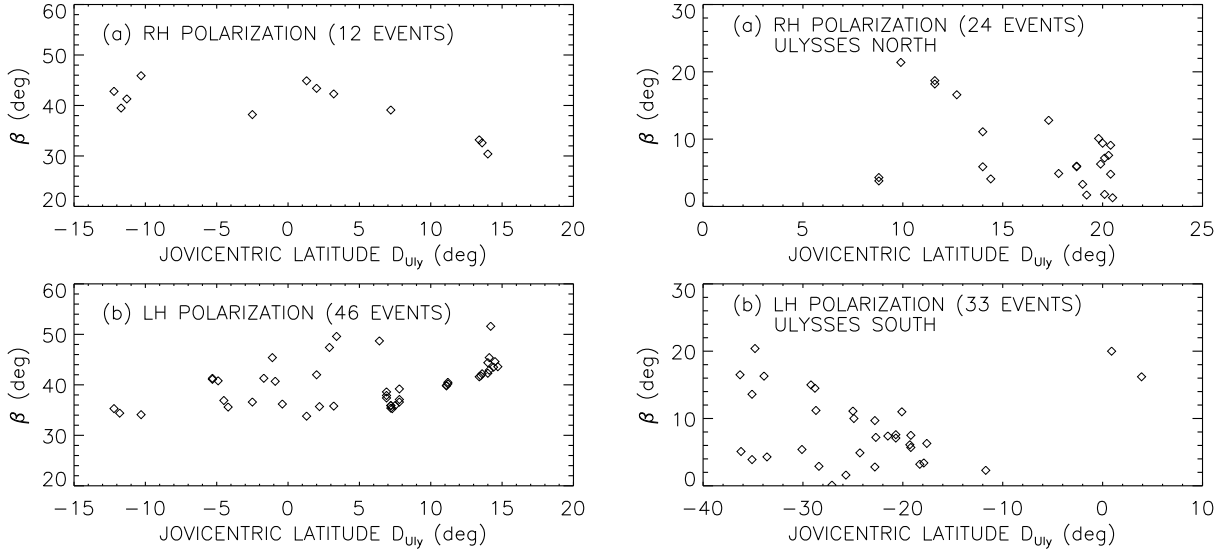


Figure 10: Left: Calculated values of emission cone half-angle β , for the HOM events represented in Figure 3, against jovicentric latitude for (a) the northern jovimagnetic hemisphere source (RH), and (b) the southern jovimagnetic hemisphere source (LH).

Figure 11: Right: Calculated values of emission cone half-angle β , for the bKOM events represented in Figure 4, against jovicentric latitude for (a) the northern jovimagnetic hemisphere source (RH), and (b) the southern jovimagnetic hemisphere source (LH).

or, indeed, at any time when Ulysses was in a southerly jovicentric latitude?

2. And, similarly, why was LH polarization only received when Ulysses was in southerly jovimagnetic latitudes and RH polarization only when Ulysses was in northerly jovimagnetic latitudes?

If the cones angles are large, there should be configurations where, as for the HOM, bKOM originating in one hemisphere of Jupiter could have been received by Ulysses when the spacecraft was in the opposite hemisphere; and yet this does not seem to have occurred during the period studied here which covers almost the whole range of jovicentric latitudes occupied by the spacecraft.

Thus it may be necessary to question the suitability of the CMI theory as an explanation of the bKOM emission process although, at present, there is no obvious alternative explanation available. This problem does not arise for the HOM, however, where the present observations appear to be consistent with previous work and in accord with a CMI model for the emission process.

5 Conclusion

We have studied the bKOM and the HOM radio emissions from Jupiter as they were observed by the URAP experiment on board Ulysses during the period 940101 to 960229, when the spacecraft was passing from south to north of the Jovian equatorial plane at distances ranging from 4.7 to 7.2 AU. The results are summarized and compared in Table 1.

It is found that, in general, the bKOM events observed when Ulysses was in northerly jovicentric latitudes were RH polarized while events recorded when the spacecraft was in southerly jovicentric latitudes were LH polarized, the changeover taking place somewhere between $3.9^\circ \leq D_{Uly} \leq 8.8^\circ$, close to 0° jovimagnetic latitude. Occurrence probabilities for left-hand polarized events were lower than those found previously by Barrow and Lecacheux [1995] but similar in distribution. For the right-hand polarized events, however, the distribution was different, the so-called main peak being absent or, perhaps, displaced to a higher CML.

We have seen that, in a two-dimensional CMI model, the detection of radiation at a given frequency f_c by a spacecraft at a given location specified by δ , determines a unique value of β for an assumed value of L and a given field model. This is not true for a three-dimensional model. If the emission cones are assumed to be directed towards Ulysses, calculated values of β for the bKOM events reported here, assuming values of $L = 15$ and $f_c = 52$ kHz, are all found to be less than about 25° . Larger values of β are possible, in principle, but then the source must be near the limb of the planet with respect to the observer. This raises difficulties concerning the polarization sense observed to either side of the jovimagnetic equatorial plane.

It may be necessary to question the suitability of the CMI theory as a possible explanation of the bKOM emission process although there is no obvious alternative explanation available at the present time.

The HOM observations are generally consistent with previous work based upon URAP observations close to encounter and Voyager observations and in accord with a CMI emission process.

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