JUPITER'S LOW-FREQUENCY RADIO SPECTRUM: FILLING IN THE GAPS

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Abstract

We report observations by the WAVES experiment on the Wind spacecraft of Jupiter's low frequency decameter wave radio emission. These observations were made with the unusual combination of low D_E and low frequency. With these observing parameters, the Io-C and Io-D sources are very dominant over the Io-A and B sources. The arcs structures in these two sources tend to follow Io as it moves westward. We show that these sources are very likely from the southern auroral region of Jupiter as the Io footprints in the North are beyond the radio horizon.

1 Introduction

Jupiter's low frequency radio spectrum extends from near the absolute cutoff imposed by the solar wind plasma frequency (typically a few kHz) to about 40 MHz [Kaiser, 1993]. However, not all portions of this spectrum are equally well studied or understood. Below about 1.5 MHz, the two Voyager Planetary Radio Astronomy (PRA-see Warwick et al., [1977]) and the Ulysses Unified Radio and Plasma wave instrument (URAP-see Stone et al., [1992a]) have provided extensive and quite detailed measurements, including in some cases, a good knowledge of the actual source location of the emission in the Jovian magnetosphere. At frequencies above about 15 MHz, many ground-based radio observatories have contributed to the more than three decade-long data base. In the range from 1.5 to 15 MHz, ground-based observations are difficult or impossible because of the obscuring effects of Earth's ionosphere, and space-based observations until now have been limited to the Voyager PRA receivers which were plagued by spacecraft-generated interference, and the IMP-6 [Brown, 1974] and RAE [Desch and Carr, 1974, 1978] observations at a few selected frequencies. Yet it is within this very range of frequencies that (a) Jupiter's radio spectrum has its peak intensity [Carr et al., 1983], (b) the organization of the decameter wavelength (DAM) radio emissions as a function of Jovian longitude facing the observer seems to stop [Desch and Carr, 1978], (c) hectometer wavelength (HOM) emissions seem

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to reach a frequency above which they cease to exist [Boischot et al., 1981], and (d) a transition from predominantly right hand circular polarization at higher frequencies to at least equal right and left hand emissions occurs [Alexander et al., 1981].

In November, 1994, the Wind spacecraft was launched into a complex Earth orbit. Wind is part of the Global Geospace Science program designed to measure the flow of energy and matter in Earth's vicinity [Acuña et al., 1995]. Included in Wind's complement of fields and particles instruments is the WAVES experiment [Bougeret et al., 1995] which measures electric and magnetic fields from near DC to 14 MHz. The portion of the WAVES instrument which covers the frequency range of interest here is called RAD2 and, every 16 seconds, sweeps through 256 channels (20 kHz bandwidth, spaced every 50 kHz) in the range from 1.075 MHz to 13.825 MHz. RAD2 is driven by a 15-m dipole antenna.

Although WAVES' primary goal in this frequency range is to measure solar type II and type III bursts, it is also quite sensitive to Jovian emissions. There are no sources of spacecraft interference such as those that hindered Voyager PRA, so WAVES can effectively observe Jupiter continuously as long as the emission exceeds galactic background, the nominal threshold for RAD2.

2 Observations and Discussion

Although the WAVES data set begins on November 12, 1994 and continues to present, we have restricted the analysis intervals to correspond to those times when Jupiter's solar elongation angle was 90° or greater to facilitate comparison with ground-based observations. These periods are to March 1 through August 31 in 1995, and April 1 through September 30 in 1996.

During these intervals the declination of Earth (D_E) as seen by Jupiter ranged from $-3.0°$ to $-1.8°$. Ground-based observations at higher frequencies have shown that the occurrence of Jovian emissions is a strong function of D_E [Carr et al., 1983]. For example, at 16.7 MHz, the occurrence probability of detecting Jovian emissions is nearly 25 percent when D_E is at its maximum ($+3.3°$) but only about 5 percent when D_E is at its minimum ($-3.3°$). Furthermore, these large variations in occurrence probability are not uniform in System III central meridian longitude (CML) or Io phase. The traditional Io-controlled sources vary differently from one another as a function of D_E.

Figure 1 shows schematically how the WAVES observations differ from those of the ground-based observers and from the Voyager PRA. Ground-based observers have made observations over the entire range of D_E, but cannot consistently observe below 15 MHz. The Voyager PRA observations covered the entire Jovian frequency range, but were restricted by the spacecraft trajectories to a range of positive D_E that barely overlapped with the ground-based observations. The gap in D_E - frequency space is being filled in by the WAVES observations.

Figure 2 shows the occurrence probability of emissions in the 2-14 MHz band for the two opposition intervals analyzed. The catalog of Jovian emissions used to create Figure 2

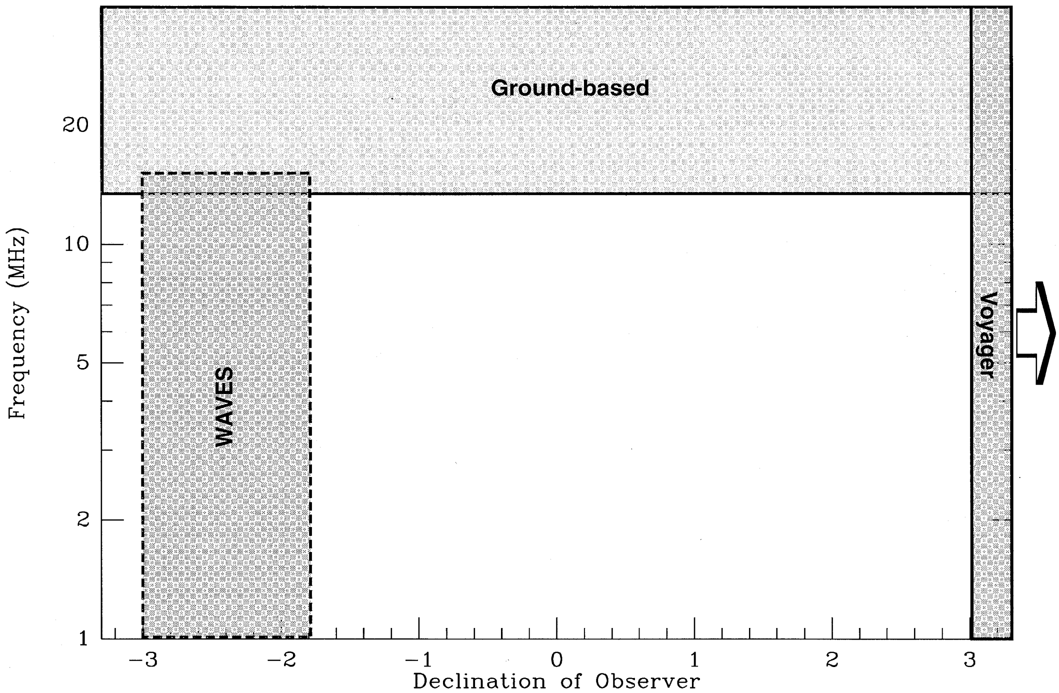

Figure 1: Contrast between the observing parameters D_E and frequency for ground-based observers, the Voyager PRA observations, and the Wind/WAVES observations.

was made by visual examination of the WAVES daily summary plots and has a detection threshold of about 10^{-20} W m^{-2} Hz^{-1}. The display format of Figure 2 is the standard central meridian System III longitude versus the Io phase (departure of Io from superior conjunction) with accompanying histograms of occurrence in longitude (top) and Io phase (right). Most, if not all, of the emission detected by WAVES is Io-controlled, consistent with the RAE results reported by Desch and Carr [1978]. Both WAVES and RAE have relatively high threshold sensitivity, so that weaker emissions not controlled by Io are not observed.

For comparison, Figure 3 shows, in the same format as Figure 2, the 18-22 MHz observations from the University of Florida Observatory taken during the 1968-1972 apparitions when D_E was approximately the same as that for the WAVES observations. The threshold for the Florida observations is about $4 \cdot 10^{-22}$ W m^{-2} Hz^{-1}, allowing both Io-controlled and non Io-controlled emissions to be observed.

With the usual assumption that there have been no large long-term changes in the Jovian radio morphology between 1968-72 and present, there are clearly fundamental differences between the occurrence probabilities of the Io-controlled emissions shown in Figs. 2 and 3 which must be a function of frequency. The most dominant "sources" at the higher frequencies are the so-called Io-B source centered at about 140° System III and 90° Io phase, Io-A at 230° System III and 240° Io phase, and Io-C at about 330° and 240°, respectively. The Io-A and B sources are not dominant in the WAVES data, and Io-C is extended in System III longitude with its highest occurrence probability shifted some $40 - 50°$ relative to its 18-22 MHz position. Also in the WAVES data a strong source

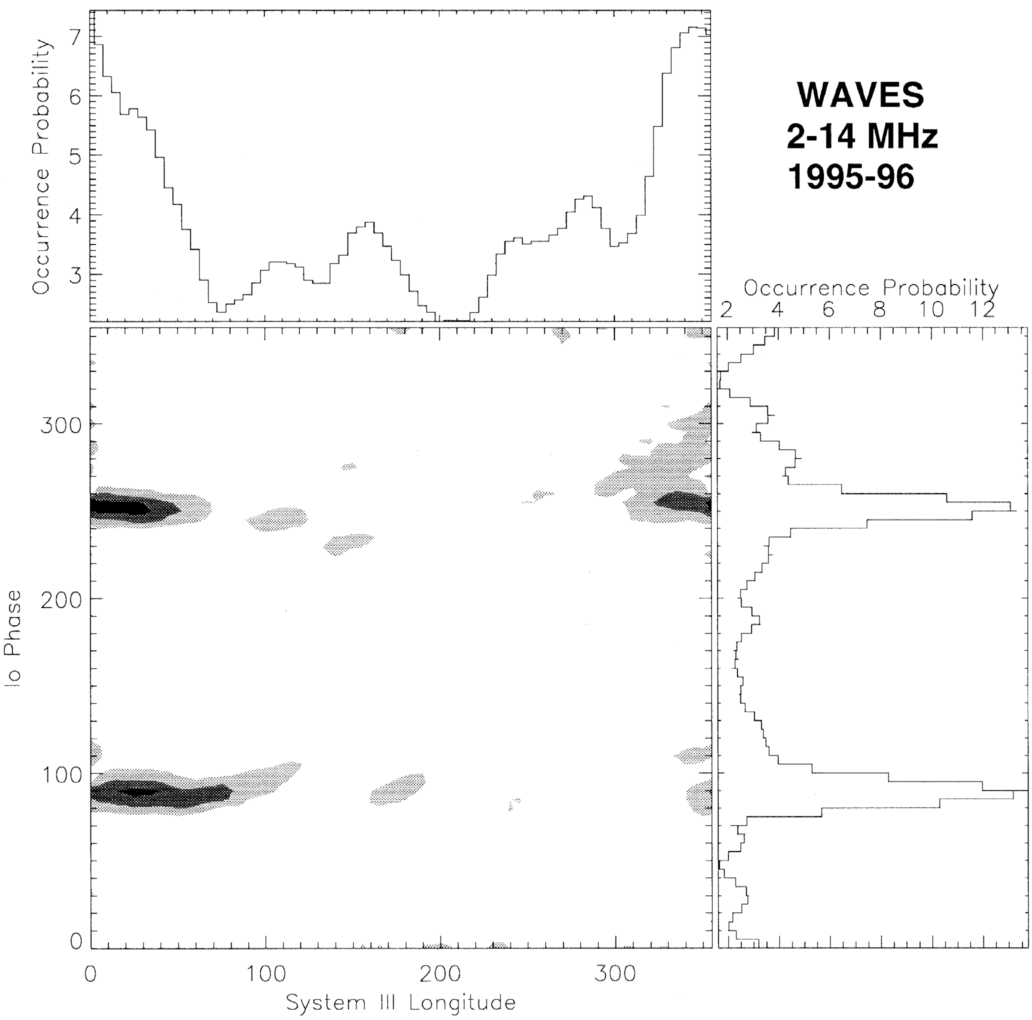

Figure 2: Occurrence probabilities for the WAVES 2-14 MHz observations during the Jupiter oppositions of 1995-96.

at about 20° System III and 90° Io phase appears, near the location of the Io-D source sometimes observed at higher frequencies. These differences are most noticeable in System III longitude as can be seen by comparing the histograms at the top of Figures 2 and 3. The occurrence probabilities in Io phase (right histograms in both Figures) are very similar in shape although there is about a factor of two difference in the absolute occurrence probability, much of which is due to the threshold sensitivity differences between WAVES RAD2 and the Florida array.

Figure 4 shows three examples of dynamic spectra from the WAVES instrument corresponding to the Io-D emission. This emission component is characterized by a vertex early arc or series of arcs with the vertex frequency equal to about 5 MHz. The System III central meridian longitude in view when Io phase reached 90° is indicated in each panel. As this point occurs at successively later longitudes, the main arc also moves to later longitudes, and the "sharpness" of the vertex may increase. Movement of the arc to later longitudes is similar to the behavior reported by Boischot et al. [1981] for the PRA

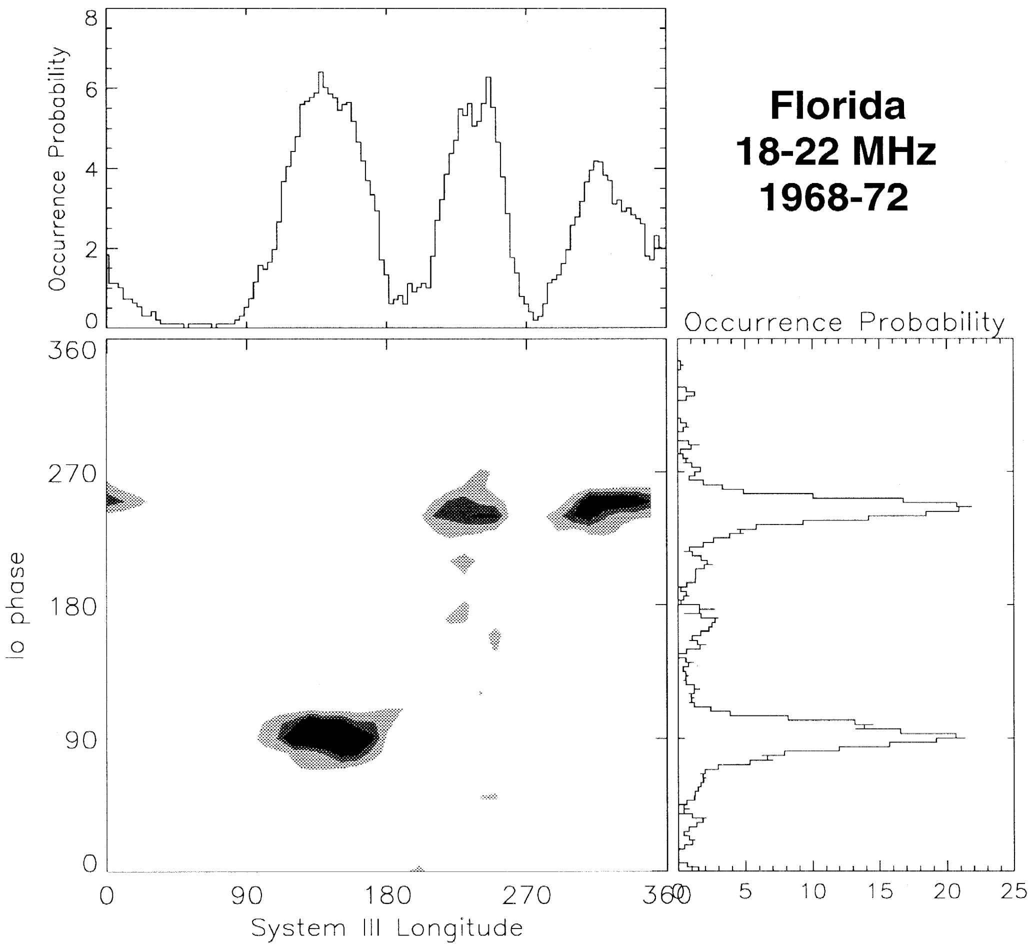

Figure 3: University of Florida occurrence probabilities for the 18-22 MHz Jovian observations during the 1968-72 interval when D_E was similar to that in Figure 2.

observations at large D_E where the arc tended to "follow" Io westward, but at about half the rate. In Figure 4, the location of the Io=90° longitude increases by about 40° from the top panel to the bottom, whereas the position of the vertex frequency of the arc increases by about 20°.

Figure 5 shows examples of Io-C for times when Io phase is 255°. The Io-C emission consists of a series of vertex late arcs with vertex frequency at approximately 8 MHz. Like the Io-D emission shown in Figure 4, the Io-C arcs occur at more westerly longitudes as the Io phase=255° also moves westward, although the difference is substantially less than a factor of two. The Io=255° longitude moves westward by about 120° between the top and bottom panels, whereas the arcs move about 90°.

Much has been written about the source locations of the various Io-controlled radio emissions [Carr et al., 1983]. Virtually all of these discussions center on the assumption that the emission takes place at the electron gyrofrequency at the appropriate altitude on the Io flux tube. From this assumption, the observed maximum frequency and polarization sense suggest that Io-A and B come from the northern hemisphere and Io-D from the southern. Io-C could, in principle, come from either.

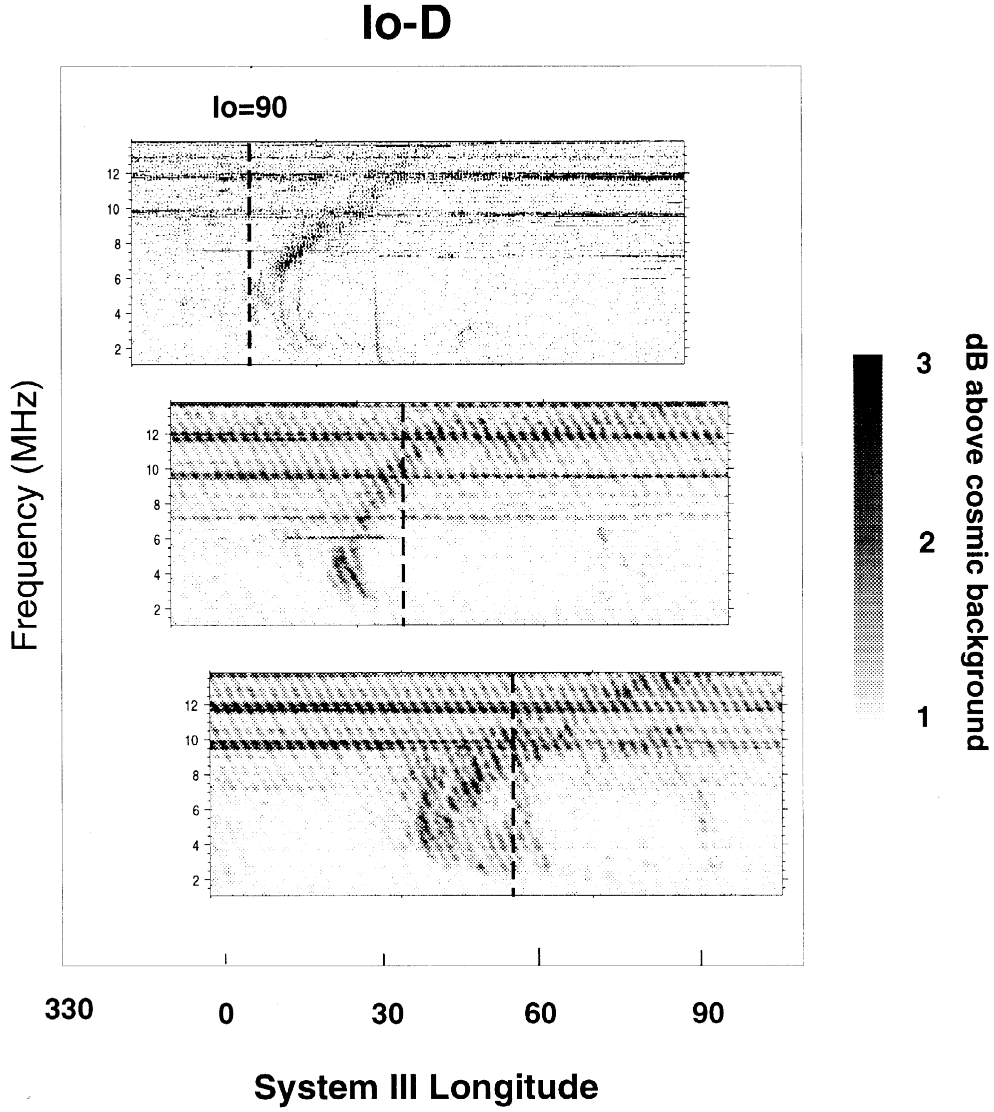

Figure 4: Examples of Io-D emission observed by WAVES. The position of the Io=90° longitude is shown. The Io-D arc tends to follow Io westward at about half Io's rate.

In Figure 6, we approach this problem of source location in a somewhat different way. For each WAVES event, we have determined the foot points, North and South, of the Io flux tube, using the "O_6" magnetic field model of Connerney et al. [1992] at an altitude corresponding to 8 MHz, the middle of the RAD2 frequency range. We have used a coordinate system that gives these footprints as a function of departure from Jovian central meridian and Jovigraphic latitude. We then plotted contours of occurrence probabilities for the two cases, emission from the North in the left panel and emission from the South in the right panel. For both of these location assumptions, the emission occurrences are nicely organized. However, also plotted in Figure 6 is the *visible* horizon line, which would also approximately correspond to the *radio* horizon (the radio horizon or extraordinary mode cutoff would be somewhat closer to the equator than the visible horizon). The important point here is that the putative sources in the northern hemisphere are all

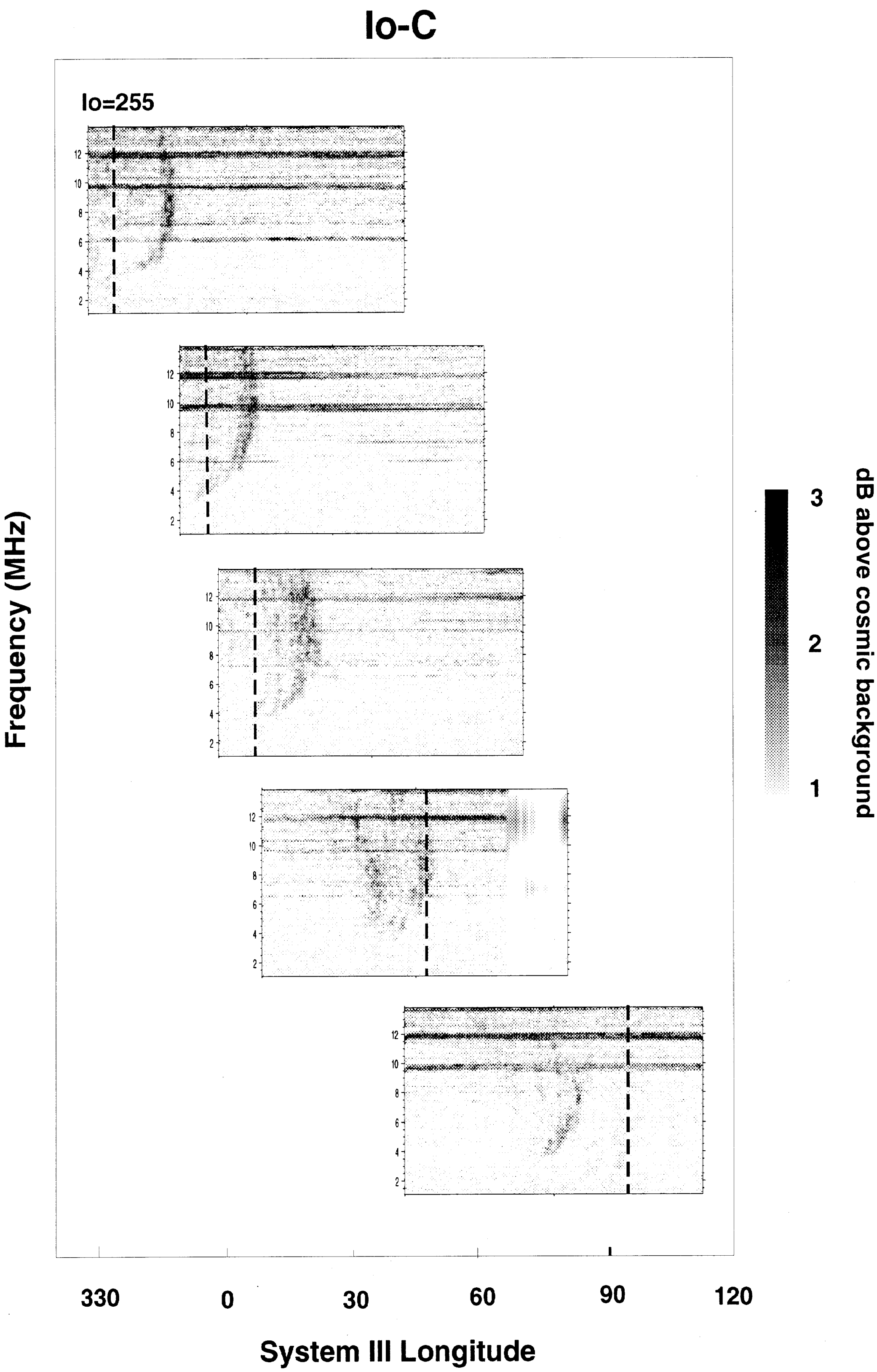

Figure 5: Similar to Figure 4 but for WAVES Io-C observations. The Io=255° longitude point is indicated. Again, the arcs follow Io westward, but at much more than half the rate.

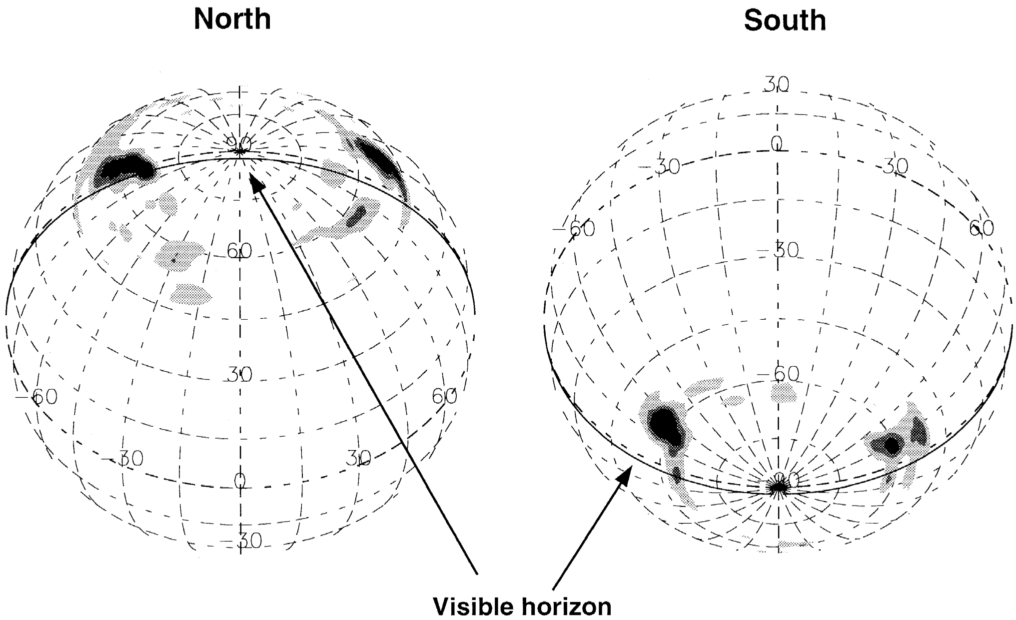

Figure 6: Contours of occurrence probability for the WAVES 2-14 MHz catalog displayed as a function of the position of Io's footprint at an 8 MHz altitude for both the northern (left) and southern (right) hemispheres. The Io footprint position is in terms of angle from central meridian and Jovigraphic latitude. Also shown is the visible horizon line. The possible sources in the North are all invisible to WAVES, implying that the IO-C and D emissions must be from the South.

beyond the visible horizon: the emissions could not propagate to the observer. Therefore, we believe the Io-C and D emissions observed by WAVES must come from the southern hemisphere.

3 Summary

We have presented observations made by the WAVES experiment on the Earth-orbiting Wind spacecraft of Jupiter's low frequency (2-14 MHz) radio emissions. This combination of low frequencies and low ($-3.0°$ to $-1.8°$) D_E that occurred during the two year interval studied (1995-96) have helped to fill in a gap in observations in these two parameters. We find that Io-C and D emissions completely dominate the WAVES data. Io-A and B that are very strong at higher frequencies and higher D_E contribute very little to the occurrence probability observed by WAVES. However, some similarities with Voyager PRA observations in the same frequency range but at high D_E still persist, namely, the tendency of dynamic spectral arcs to "follow" Io's footprint as it moves westward. We have also presented an argument based on the visibility of the Io footprint that the Io-C and D emissions observed by WAVES must come from the southern auroral zone.

If the Wind spacecraft is allowed to have an extended mission (beyond 1997), the D_E space will be completely filled in to join with the PRA observations.