JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. A7, PAGES 16,053-16,062, JULY 1, 2000

Cassini and Wind stereoscopic observations of Jovian nonthermal radio emissions: Measurement of beam widths

M. L. Kaiser
NASA Goddard Space Flight Center, Greenbelt, Maryland

P. Zarka
Observatoire de Paris, Meudon, France

W. S. Kurth, G. B. Hospodarsky, and D. A. Gurnett
Department of Physics and Astronomy, University of Iowa, Iowa City

Abstract. During two intervals in 1999, simultaneous observations of Jupiter's decametric and hectometric radio emissions were made with the Cassini radio and plasma wave instrument (RPWS) and the radio and plasma wave instrument (WAVES) on the Wind spacecraft in Earth orbit. During January the Jovian longitude difference between the two spacecraft was about 5°, whereas for the August-September Earth flyby of Cassini, the angle ranged from 0° to about 2.5° (the Jovicentric latitudinal difference was <0.3° during both intervals). With these separations the instantaneous widths of the walls of the hollow conical radiation beams of some of the decametric arcs were measured by cross correlating dynamic spectra. The results suggest that the typical width is approximately 1.5° ±0.5°. The conical beams seem to move at Io's revolution rate for Io-controlled arcs. Additionally, some of the nonarc hectometric wavelength emissions show some properties of both wide and very narrow beam widths.

1. Introduction

During the Voyager 1 and 2 flybys of Jupiter in 1979, the two spacecraft were never able to make simultaneous stereoscopic observations of the Jovian nonthermal radio emissions using the planetary radio astronomy (PRA) instrument. This was due mostly to the data collection schedule that permitted only one spacecraft at a time to be in a high enough data rate to make meaningful observations. Furthermore, Earth orbiting spacecraft, which often can detect Jovian radio emissions, have very little angular separation from one another as seen from Jupiter. This means that the intrinsic beam widths of Jupiter's multitude of radio sources have never been measured stereoscopically.

From the individual Voyager spacecraft observations, the PRA team discovered that a large part of Jupiter's emissions in the range from a few to 40 MHz is organized into thin "arc-like" structures when viewed as a frequency-time dynamic spectrum [*Warwick et al.*, 1979a,b]. Several theories [*Goldstein and Thieman*, 1981; *Pearce*, 1981; *Staelin*, 1981; *Warwick*, 1981] on the formation of arcs concentrated on a hollow cone model of the radiation beam(s). Hollow cone radiation beams where emission is confined to the thin walls of the cone are predicted by most Jovian emission mechanism theories [*Smith*, 1976; *Zarka*, 1998]. As depicted in Figure 1, the hollow cones have their vertices along a Jovian magnetic field line rotating with the planet's period of 9.92 hours, or along a flux tube threading through the satellite Io and rotating with a period of 42.5 hours. The altitude along the field line or flux tube is fixed where the electron gyrofrequency (more precisely, the extraordinary mode cutoff frequency) equals the radiation frequency. As the field line or flux tube corotates past the observer, radiation from the cone walls will pass by the observer, who will see the arc-like structures in the frequency-time plane. Matching sets of arcs are caused when the leading wall of the cone passes (vertex early or open parenthesis) and then when the trailing wall passes (vertex late or close parenthesis).

All of Jupiter's decameter (DAM) wavelength emissions are categorized according to whether Io's position has a strong influence (Io-controlled) or weak or nonexistent influence (non-Io-controlled). These two major categories are further subdivided into "sources" (A, B, C, and D) as determined by concentrations of emission occurrence as a function of the observer's system III longitude and Io phase. The definitions of these sources given by *Carr et al.* [1983] are used here.

A major input to the hollow cone arc theories is the thickness of the cone walls. Most researchers have taken the duration of a given arc as a measure of its thickness. Observationally, one would expect to observe an arc simultaneously (after correction for light travel time

Paper number 1999JA000414.
0148-0227/00/1999JA000414$09.00

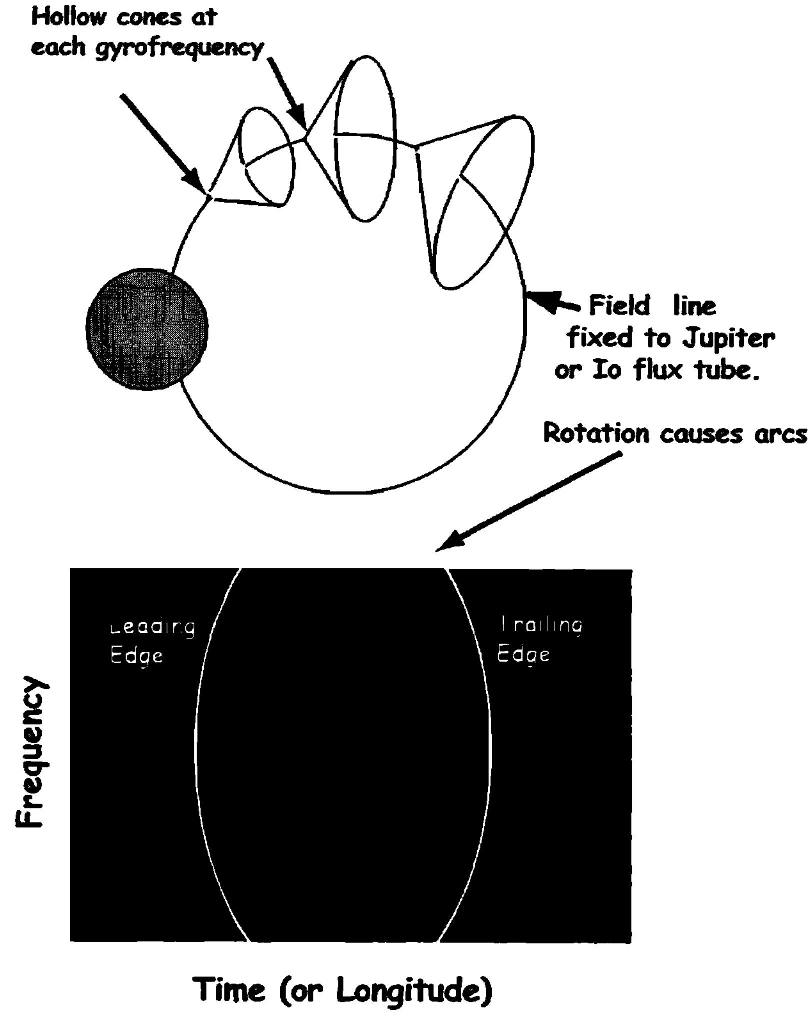

Figure 1. Illustration of hollow conical beams distributed by altitude along a magnetic field line rotating with Jupiter's period of 9.92 hours or a flux tube associated with Io rotating at its 42.5 hour period. The vertex of each cone is at the extraordinary cutoff frequency, which is essentially the same as the electron gyrofrequency. Emission is confined to the walls of the cone. As the field line or flux tube rotates through the field of view, a pair of arcs is observed in the frequency-time plane, with the leading cone wall causing a "vertex early" or open parenthesis arc and the trailing wall causing a vertex late arc. The opening angle of the cones is likely a function of frequency, in part due to variations in plasma density with altitude in the source region.

differences) by two spacecraft provided their angular separation as seen from Jupiter is less than the cone wall thickness. However, if the wall thickness is considerably less than the angular separation, then the arcs will not be observed simultaneously but will be delayed by the amount of time it takes for the cone attached to a Jovian magnetic field line or Io flux tube to rotate through the angle (again, after correction for light travel time differences).

At frequencies near and below 1 MHz, a different radio component is dominant, the so-called hectometric component (HOM) [*Carr et al.*, 1983; *Ladreiter and Leblanc*, 1992; *Zarka*, 1998]. HOM likely originates from somewhat higher latitude field lines than the Io-controlled arc emissions [*Ladreiter et al.*, 1994; *Reiner et al.*, 1993] and appears in frequency-time dynamic spectra as considerably broader features than the arcs. In order to observe HOM emission, the observer must be in a narrow band (approximately 10° range) of Jovicentric latitudes [*Alexander et al.*, 1979]. *Ladreiter and Leblanc* [1990a,b] showed that the latitudinal beaming is the consequence of a hollow conical beaming pattern and propagation effects through the Io plasma torus. However, HOM may be simultaneously active on a large set of auroral field lines, so a distant observer would detect the combined radiation pattern.

2. Instrumentation

Both the Cassini radio and plasma wave science (RPWS) instrument [*Gurnett et al.*, 2000] and the Wind radio and plasma wave (WAVES) instrument [*Bougeret et al.*, 1995] cover a frequency range from near dc to 14-16 MHz. For the present work, only the highest-frequency portion of each instrument was used and that is all we will describe here.

The Cassini spacecraft, launched in October 1997, is destined for Saturn, where it will arrive in 2004. On board are a complete suite of visible, IR, and UV imagers and a host of fields and particles instruments, including the RPWS instrument. The upper frequency range of the RPWS instrument consists of two sets of four analog receivers with a digital-processing unit. The receiver can be tuned over the frequency range from 3.6 kHz to 16.1 MHz. For the present study, only the upper two bands were used; HF1 covers the range from 125 kHz to 4.125 MHz in multiples of 25-kHz steps, while HF2 covers the range from 125 kHz to 16.1 MHz in 50N-kHz steps. The receiver, during the period of interest here, was connected to a dipole antenna of 18.52 m length. RPWS sampled the spectrum with 200-kHz resolution once every 64 s for the events shown in Figures 3, 4, and 6, and once every 10 s for the events shown in Figures 5, 7, and 8.

The Wind spacecraft was launched in November 1994 into a complex Earth orbit [*Acuña et al.*, 1995]. Among its many fields and particles instruments is the WAVES instrument, designed primarily to observe solar radio and in situ plasma waves. Two swept frequency receivers cover WAVES' highest frequency range. RAD1 is connected to a 100-m tip-to-tip spin plane dipole, and operates in the range 20 kHz to 1040 kHz in 256 channels spaced every 4 kHz. RAD2, which is used for most of the comparisons with RPWS, is connected to a 15-m tip-to-tip spin plane dipole and covers the range from 1.075 MHz to 13.825 MHz in 256 steps spaced every 50 kHz. During the interval of study here, RAD1 was operated in a mode where a subset of 32 channels was used (primarily for solar studies). RAD2 sweeps through the 256 channels every 16.192 s, but 1-min averages are used here to reduce the effects of spacecraft spin modulation.

Both RPWS and WAVES are capable of detecting cosmic background throughout the frequency range used here. Owing primarily to a quieter receiver, RPWS is somewhat more sensitive than WAVES above 1 MHz. This is especially true in the range from about 5.5 to 8 MHz, where WAVES' sensitivity is degraded due to distortion of the antenna pattern by a spacecraft boom. Below 1 MHz, WAVES is more sensitive because of the much longer antenna used. For the events chosen for this study, none of these sensitivity differences are important.

3. Viewing Geometry

In order to achieve enough velocity to reach Saturn in 2004, the Cassini spacecraft needed gravitational assists from two close passes of Venus, one of Earth, and a future one at Jupiter (late 2000). Figure 2 shows the viewing geometry that was in effect for the two intervals of Cassini observations. The January 1999 interval occurred while Cassini was at opposition, which enabled the high gain antenna to be pointed at Earth to support science telemetry. During this time, Cassini was approximately 0.5 AU from Earth in the antisunward direction. In this opposition interval, approximately 2 weeks of RPWS data were obtained, during which Jupiter's solar elongation changed from 71° east to 59° east as viewed from Earth. The Jovicentric longitudinal separation between Earth (the Wind spacecraft is close enough to Earth so that we can consider their positions the same) and Cassini was about 5.1° to 5.4° throughout the period, with Cassini being at higher west longitudes. The Jovicentric latitude difference was always less than 0.3°, with Cassini being northward of Earth. The light travel time difference from Jupiter to Earth and Cassini ranged from 175 s to 100 s during the period, Earth being closer to Jupiter.

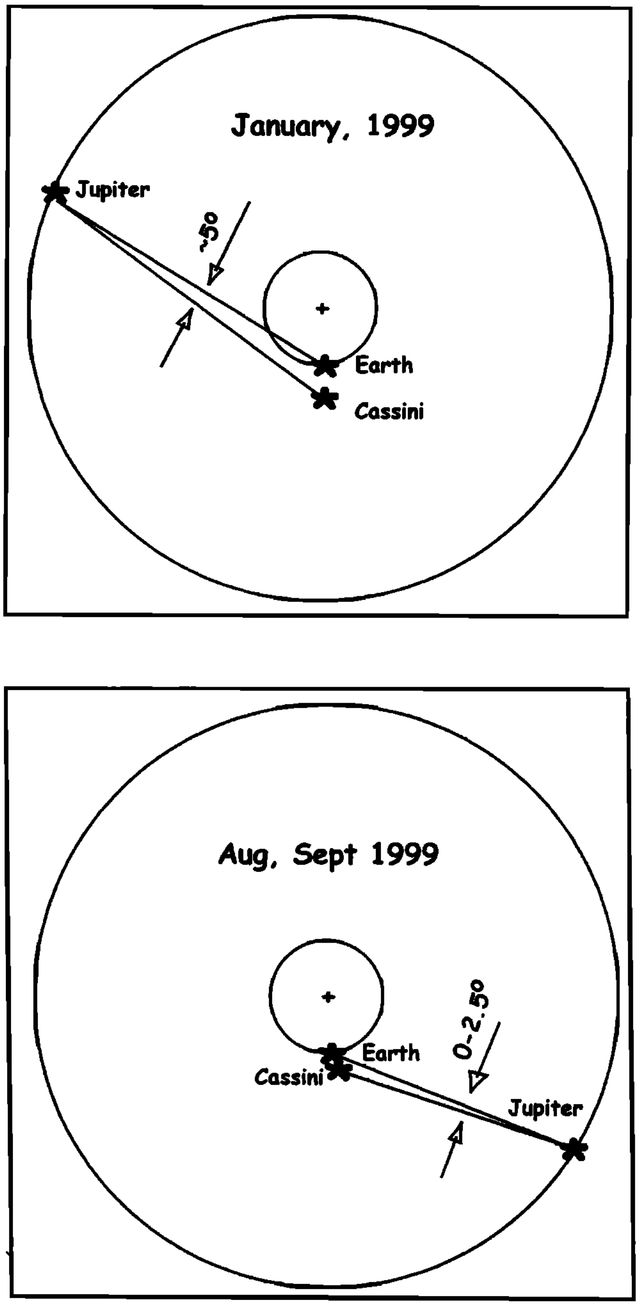

Figure 2. The relative locations of Jupiter, Earth (hence Wind), and Cassini for (top) the January 1999 interval and (bottom) the August-September 1999 interval displayed in a coordinate system fixed on the Earth-Sun line.

For the August-September interval a gravitational assist for Cassini was achieved by a close flyby (less than 1200 km) of Earth. Approximately 1 month of data was obtained by RPWS during this flyby interval (August 15 – September 14), during which Jupiter moved from elongation 106° west to 136° west, while the Jovicentric longitudinal difference between Earth and Cassini ranged from 0° to about 2.5°, with Cassini being at lower west longitudes. The Jovicentric latitude difference was essentially 0° (≤0.02°). The light travel time difference ranged from zero to just over 1 minute, Earth being more distant from Jupiter.

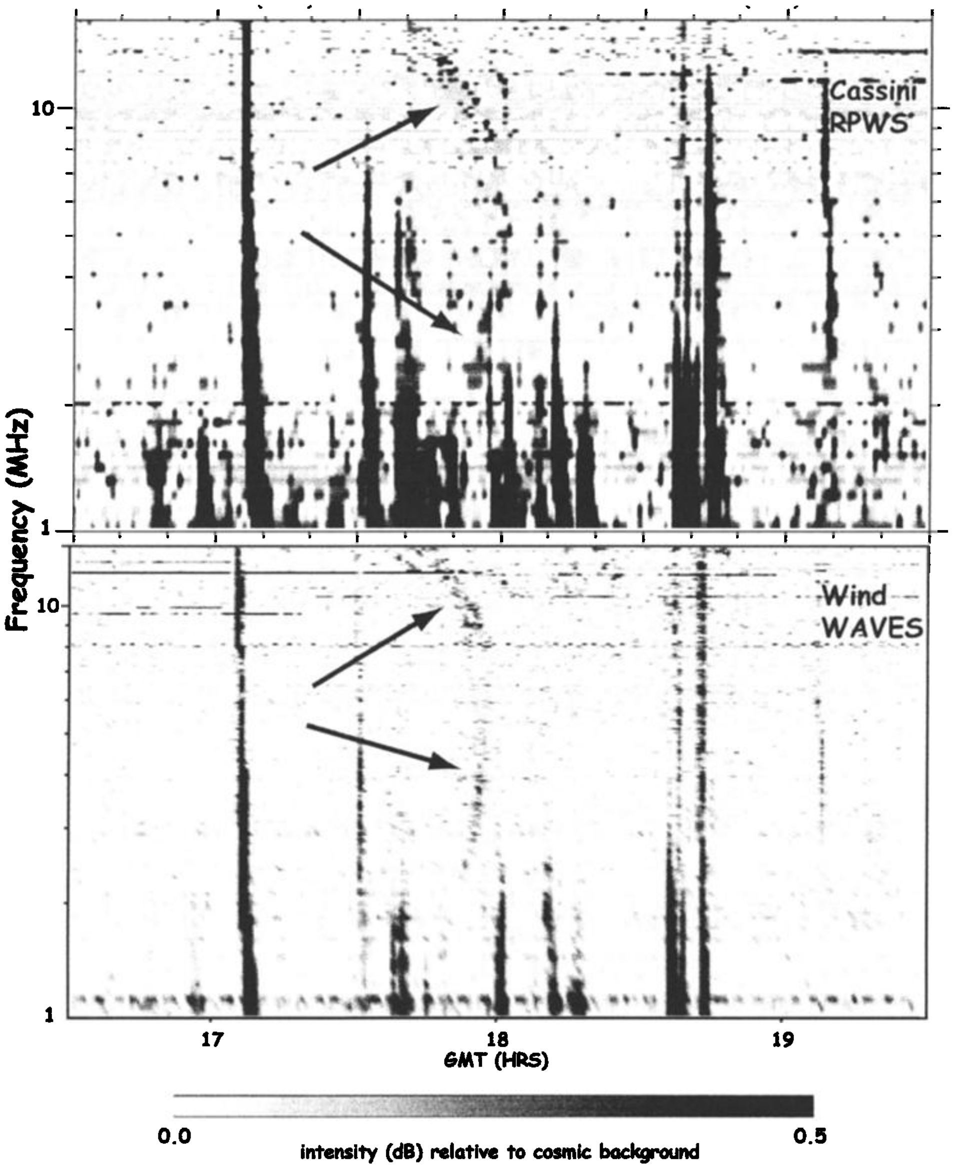

Figure 3. Three hours of data on August 25, 1999 from the highest frequency portion of (top) the Cassini RPWS instrument and (bottom) the Wind WAVES instrument displayed as a frequency-time dynamic spectrum with relative intensity above cosmic background coded as a white to black scale. The intense vertical streaks are type III solar bursts. The horizontal striations are man-made short-wave transmitters. The system III longitude and Io phase at 1800 were 284° and 59°, respectively, as seen by Wind.

4. Observations

During the two observing episodes, the number of DAM and HOM radio events was quite low so that the total number of simultaneous measurements was small. Additionally, most events were very weak, typically just slightly above cosmic background. Nevertheless, there were enough "simultaneous" events to permit some beam width measurements. Measurements of time differences and resulting uncertainties between the observations from the two spacecraft were obtained by cross-correlating the observed dynamic spectra after first binning them on identical time-frequency grids and removing type III solar bursts.

4.1 Arc Emissions

Figure 3 shows dynamic spectra from RPWS (1-16 MHz) and WAVES (1-14 MHz) taken on August 25, 1999, when the two spacecraft were only 0.6° apart in Jovian longitude and at essentially the same Jovigraphic latitudes. The vertex late (i.e., close parenthesis) arc observed by the two instruments is very weak, so the scale is stretched to only show the range from 0 to 0.5 dB above cosmic background. The often saturated vertical streaks are type III solar bursts, which were numerous throughout the August-September time interval. The occasional horizontal streaks, particularly apparent above 8 MHz, are man-made short-wave transmitters [*Kaiser et al.*, 1996]. The cross-correlation technique indicates that the observed arc is simultaneous to within ± 1 pixel, which is about ± 1 min. The light travel time difference was 23 s, with Cassini nearer to Jupiter. The time for Jupiter to rotate through the 0.6° angle would be almost exactly 1 min and for Io or an Io flux tube to move through the same angle would be 4.25 min. This all strongly suggests that the arc beam

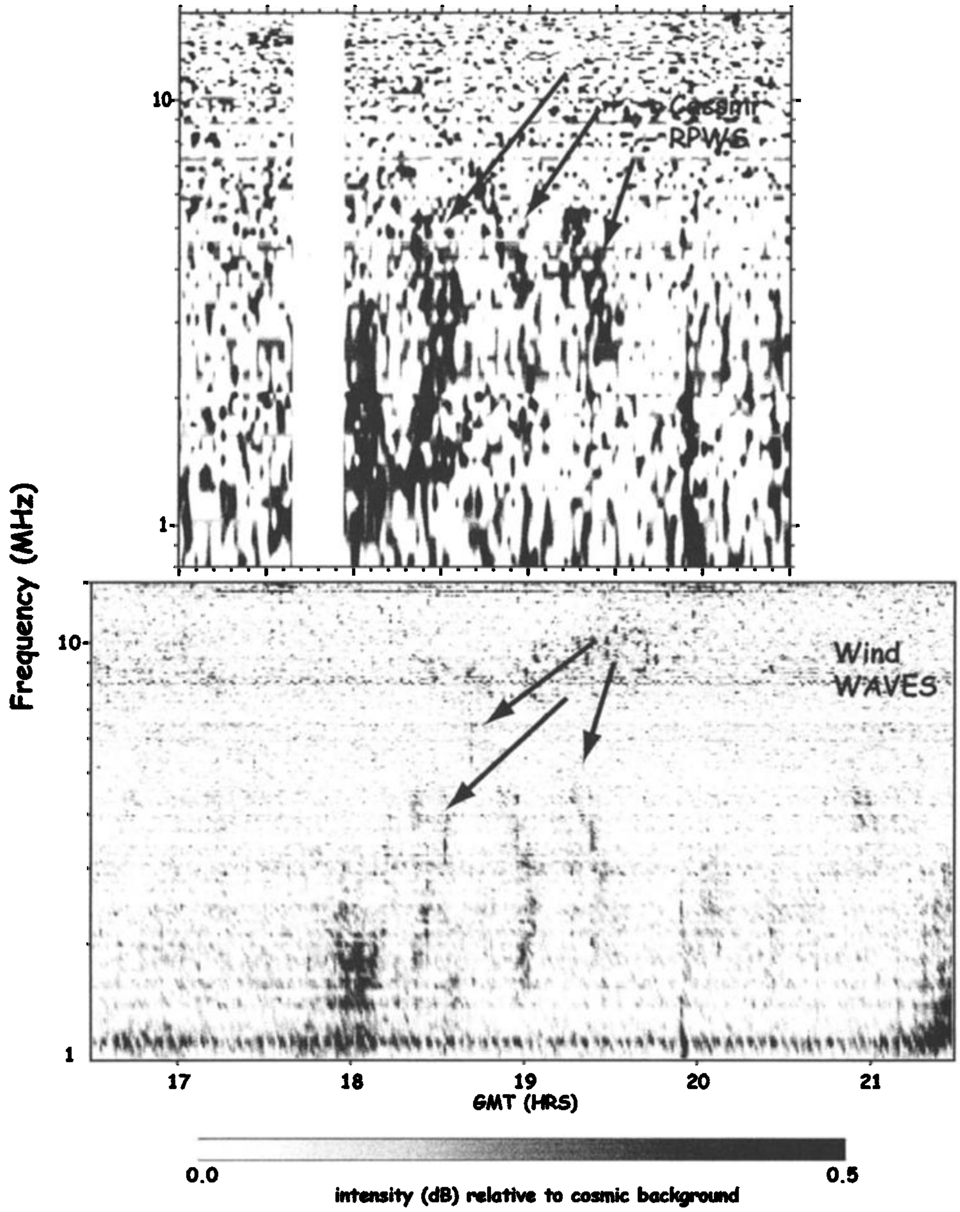

Figure 4. Five hours of data on September 5, 1999, displayed in the same format as Figure 3. The three vertex late arcs are just detectable above cosmic background. The system III longitude and Io phase at 1900 were 178° and 147°.

"simultaneously" illuminates both Cassini and Wind. The Jovian system III longitude of Wind at 1800 was 284°, and the Io phase was 59° (sub-Io system III longitude of 45°); thus this event would be classified [*Carr et al.*, 1983] as a non-Io A event.

Figure 4 shows a series of three even weaker arcs observed on September 5, 1999, when the two spacecraft were 1.69° apart in Jovian longitude and about 0.01° in Jovicentric latitude. For this event the light travel time difference was just over 1 min. The time for Jupiter to rotate through the 1.69° angle would be 2.8 min and for Io or an Io flux tube to move through the same angle would be nearly 12 min. Again, cross-correlation of the dynamic spectra indicates that the three arcs are simultaneous to within the expected light travel time difference (i.e., ±1 min), and are definitely not offset by 2.8 or 12 min. These arcs would be classified as non-Io B arcs, although their sense of curvature is opposite to that described by *Carr et al.* [1983]. However, *Leblanc* [1981] found that both senses of curvature can exist at nearly all longitudes for non-Io emissions.

Figure 5 shows an event that is a portion of an Io D arc, observed near the high-frequency limit of the two instruments on September 12, 1999, when the spacecraft were just under 2.5° apart in Jovian longitude (0.02° in latitude). Clearly the two events are not simultaneous (light travel time difference ~86 s). Cross-correlation indicates that the event is observed by Wind 17 ± 3 min before it is observed on Cassini. The time for Jupiter to rotate through the 2.5° angle would be nearly 4.2 min and for Io or an Io flux tube to move through the same angle would be 17.7 min. In all cases for the August-September 1999 interval, Wind would have observed any corotating beam from Jupiter or Io before Cassini. This event indicates that the beam is much narrower than 2.5°, and that the active magnetic field line at Jupiter is related to Io or the Io flux tube and not to a particular Jovian field line (rotating with the planet).

Figure 6 from the January interval shows an arc easily detected by Wind, but barely observable by Cassini. At this time the spacecraft were 5.4° apart in Jovian longitude and 0.3° in latitude. The light travel time difference was 108 s, with Wind being the closer observer. Although the arc is difficult to discern on the Cassini dynamic spectra, we estimate that Cassini observes this arc before Wind by 40 ±2 min. A corotating beam tied to a Jovian field line would have illuminated Cassini only 9 min before Wind, whereas a beam associated with Io or its flux tube would have been observed some 38.25 min earlier. Again, we have evidence for a beam width <<5.4° and tied to Io motion. This event would be classified as an Io C event. Note that the shape of the arcs seems slightly different as viewed by the two spacecraft, with the radius of curvature being tighter as viewed by Cassini. This is in agreement with the finding of *Queinnec and Zarka* [1998] that small Jovian longitude changes in the position of Io can lead to substantial changes in arc shape.

4.2 Non-arc Emissions

Jovian HOM emissions were detected on numerous occasions by the two instruments, but usually lacked any discrete features that could be used to measure time differences. However, we show two of the most intense

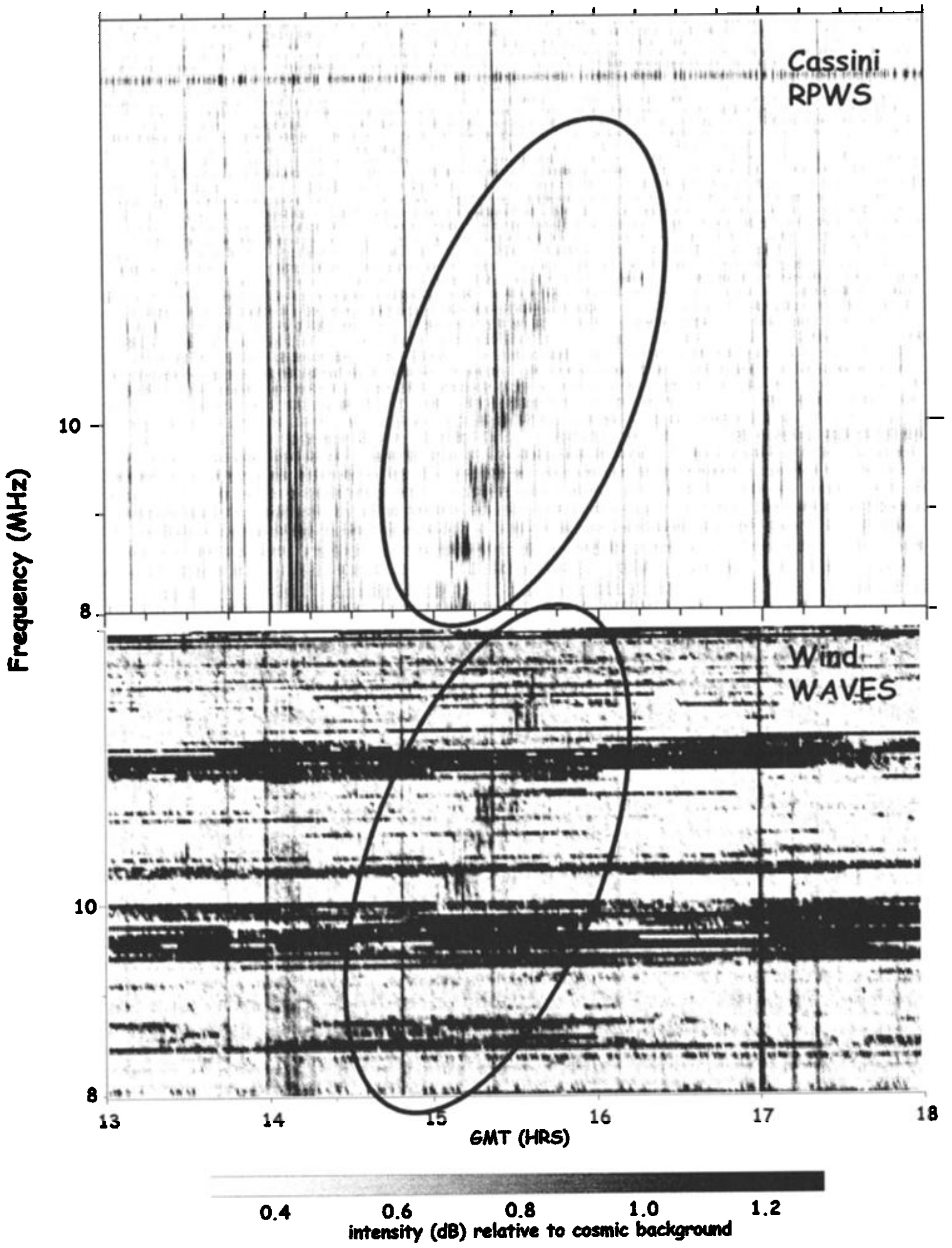

Figure 5. Five hours of data on September 12, 1999, displayed in the same format as Figure 3. The system III longitude and Io phase at 1500 were 7° and 97°.

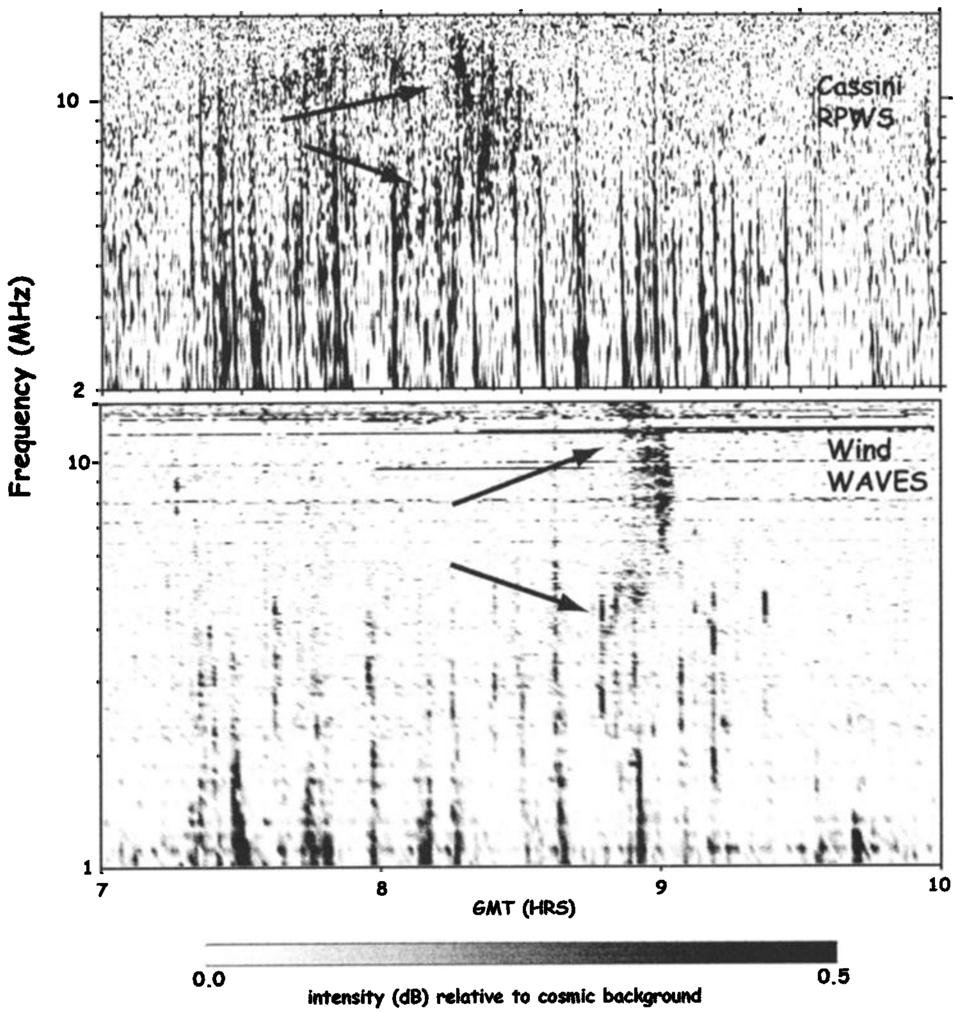

Figure 6. Three hours of data on January 17, 1999, displayed in the same format as Figure 3. The system III longitude and Io phase at 0900 were 356° and 255°.

Jovian HOM events detected during the two flyby periods that do contain enough structure to allow us to make some statements about radiation beams.

Figure 7 shows a bifurcated (in time) HOM event observed earlier in the same day (September 12) as Figure 5. This event was centered near 1 MHz and lasted for more than two hours, during which time the CML (Wind) varied from 100° to 180°. Several weak solar type III bursts were also observed during the 2-hour interval, making precise timing comparisons of HOM difficult. Nevertheless, cross-correlation of the features near the low-frequency limit (500 kHz) indicates that the event is observed nearly simultaneously (± 1 min) by the two spacecraft. This HOM event is certainly not consistent with a narrow beam associated with Io's motion, where there would be a 17 min delay. It could, however, be a narrow beam tied to a Jovian field line (<5 min expected time difference), or it could be that HOM is emitted into a beam broader than the 2.5° separation, which could be associated with either Jupiter or Io.

Figure 8 shows the most perplexing event observed during the entirety of the two Cassini Earth passes. It is also probably the most intense Jovian event observed by the two spacecraft. Again, it is an HOM event in the 1-3 MHz range, and it is the type of event called a "lane event" [*Higgins et al.*, 1995; *Lecacheux et al.*, 1980], which is probably the same as the "attenuation" band observed by the Galileo plasma waves science instrument [*Gurnett et al.*, 1992, 1998; *Higgins et al.*, 1999]. Upon initial inspection, it appears that RPWS observes this event considerably (~20 min) earlier than WAVES and over a broader frequency range. However, the apparent time difference may be illusory, caused by the dramatic difference between the two observations below 2 MHz, where WAVES' observation of the lane, so easily visible in the RPWS data, is marginal. Above 2 MHz the overall event observed by the two spacecraft seems to align quite nicely (± 1 min) although there is considerable difference in the relative intensity of individual features.

5. Discussion and Summary

We have observed a small number of Jovian DAM arcs simultaneously with the Cassini RPWS and Wind WAVES radio instruments when the two spacecraft were less than 5.4° apart in Jovian longitude. From the events presented here, a case can be made that the thickness of the walls of the hollow conical beams that cause DAM arcs is about 1.5° with an uncertainty of about 0.5°. This is essentially the same value that previous workers have surmised based on the duration of a given arc at a single frequency and equating it either to Jupiter's rotation period [*Boischot et al.*, 1981] or the Io flux tube period [*Queinnec and Zarka*, 1998; *Zarka et al.*, 1997]. Our observations also indicate that the arcs are associated with something rotating or revolving around Jupiter at a much slower rate than Jupiter's 9.92-hour rotation. The delay values shown for the Io-controlled events in Figures 5 and 6 suggest that Io or the Io flux tube is involved in these arcs, in agreement with some earlier studies [*Queinnec and Zarka*, 1998; *Zarka et al.*, 1997].

We have also observed simultaneously the Jovian HOM emission and conclude that it is not like the arc emission in that it is probably emitted into a broad beam (>5°), although our observations could be interpreted as a narrow beam tied to Jupiter's magnetic field. Our interpretation is complicated by the fact that HOM is believed to be emitted simultaneously from a broad range of Jovian longitudes [*Ladreiter and Leblanc*, 1992] so that we observe the summation of many individual hollow cones.

The HOM event shown in Figure 8 suggests that some extremely narrow beam or propagation phenomenon is involved so that even closely spaced spacecraft do not observe the same burst details. The theory presented by *Gurnett et al.* [1998] to explain the attenuation lane observed by the Galileo plasma wave science instrument, relies on coherent scattering or shallow angle reflection as the ray path from the source region over the Jovian auroral zone becomes parallel to the Jovian magnetic field at the northern or southern edge of the Io torus. This geometrical requirement might be so exacting that it could be a possible explanation for the difference of visibility of the lane by RPWS and WAVES.

It is very difficult to make general conclusions from the small number of events observed by the two instruments. The simultaneous arc events shown in Figures 3-6 are the best examples available. They are so few in number that we are hesitant to conclude that the thickness of all arc cone walls is 1.5°. The thickness is likely to be a function of refraction in the immediate source region, and this may well vary from one location to the next. Fortuitous narrow (0° to 5°) spacing of two spacecraft capable of observing Jovian radio emissions is quite rare. Future possibilities occur in the first half of 2000 when Cassini is en route to Jupiter and could make similar observations with the Galileo PWS instrument. However, the intervals when the Jovian longitude difference would permit

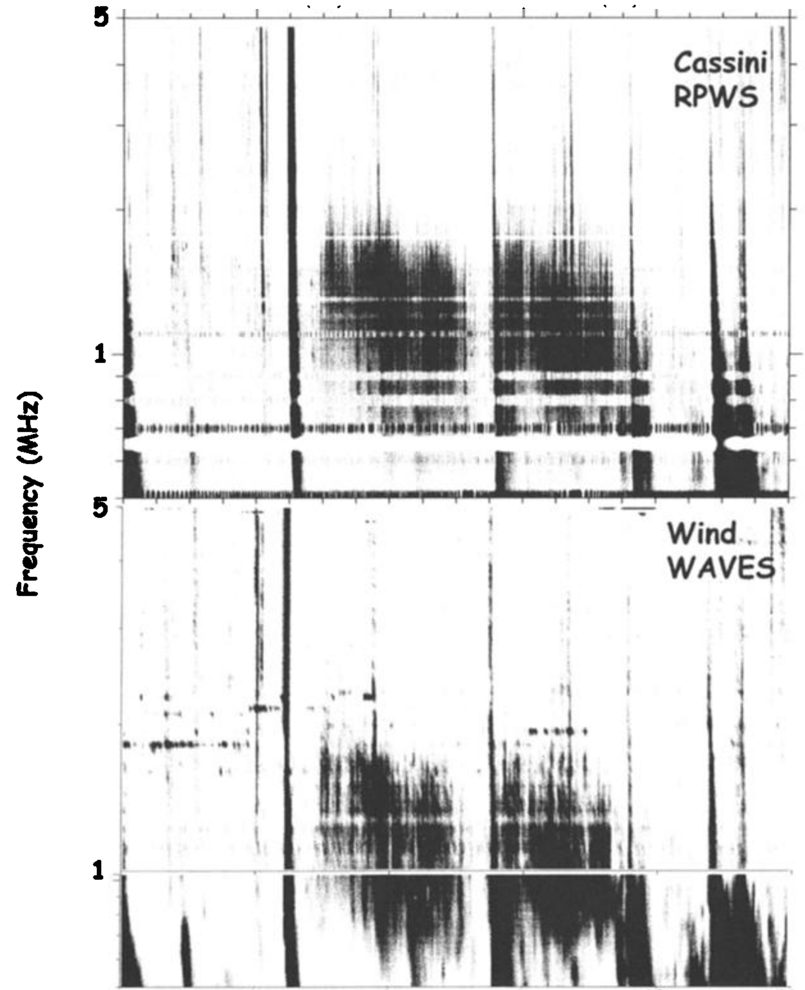

Figure 7. Five hours of data from September 12, 1999, covering the frequency range from 0.5 to 5.0 MHz and displayed in the same format as Figure 3. The relative intensity scale for RPWS and WAVES above 1 MHz is 0 to 1 dB, whereas below 1 MHz for WAVES it is 0 to 8 dB because of the use of the 100 m antenna.

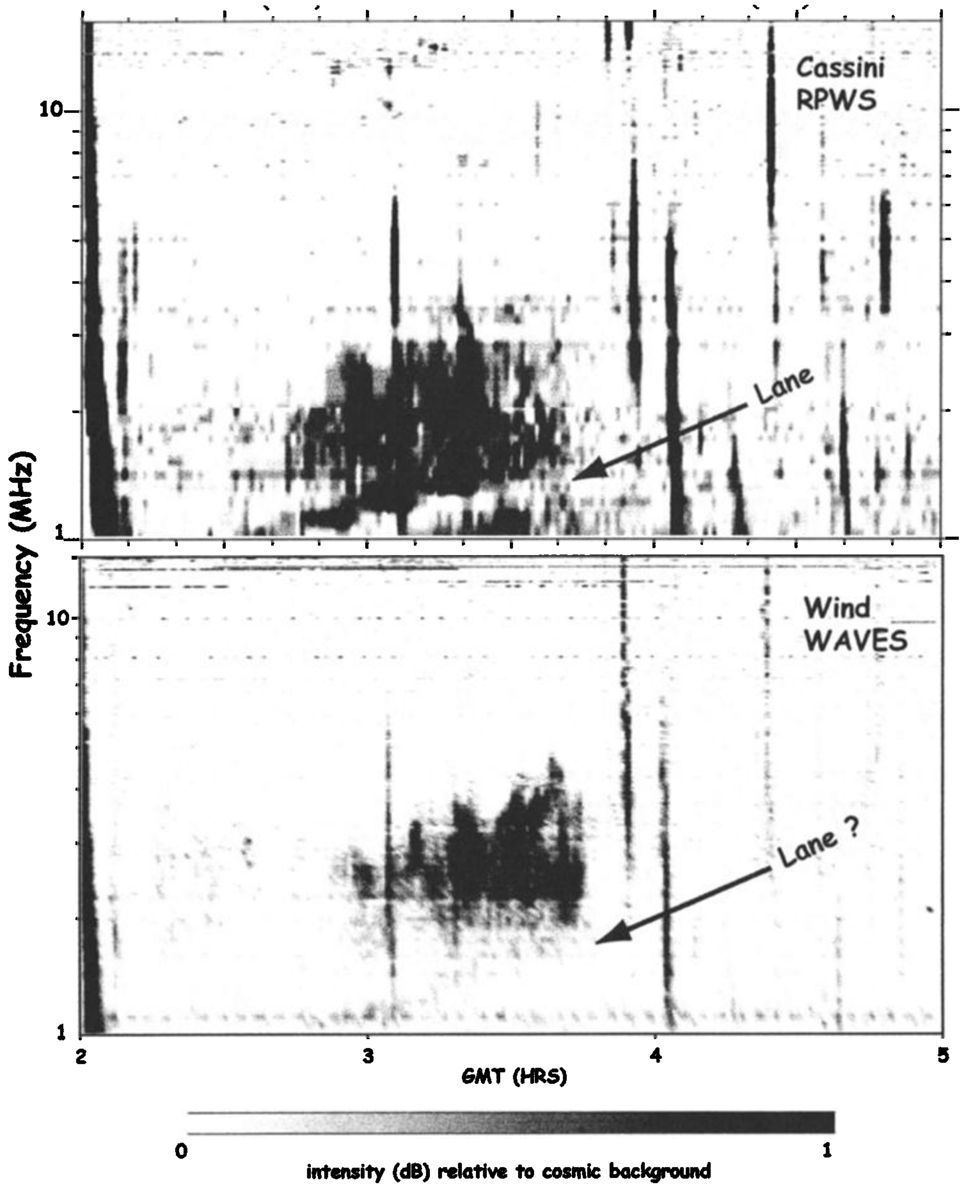

Figure 8. Three hours of data on September 7, 1999, displayed in the same format as Figure 3. The system III longitude and Io phase at 0300 were 258° and 58°.

similar measurements are very brief, and the distance to Jupiter from the two spacecraft is drastically different. Beyond that occasion, the planned solar-terrestrial relations observatory (STEREO) Mission (launch in 2004) might be able to make similar measurements.

Acknowledgments The authors wish to thank Terry Averkamp, and Joe Groene of the University of Iowa for their assistance with the Cassini data. The postlaunch U.S. mission operations and data analysis phase of the Cassini investigation is supported by NASA through contract 961152 with the Jet Propulsion Laboratory. The Observatoire de Paris contributions were supported by Centre National d'Etudes Spatiales.

Janet G. Luhmann thanks C. H. Barrow and another referee for their assistance in evaluating this paper.

References

Acuña, M.H., K.W. Ogilvie, D.N. Baker, S.A. Curtis, D.H. Fairfield, and W.H. Mish, The Global Geospace Science Program and its investigations, in *The Global Geospace Mission*, edited by C.T. Russell, p. 5, Kluwer Acad., Norwell, Mass., 1995.

Alexander, J.K., M.D. Desch, M.L. Kaiser, and J.R. Thieman, Latitudinal beaming of Jupiter's low frequency radio emissions, *J. Geophys. Res.*, *84*, 5167, 1979.

Boischot, A., A.' Lecacheux, M.L. Kaiser, M.D. Desch, J.K. Alexander, and J.W. Warwick, Radio Jupiter after Voyager: An overview of the planetary radio astronomy observations, *J. Geophys. Res.*, *86*, 8213, 1981.

Bougeret, J.-L., et al., The Wind/WAVES instrument, *Space Sci. Rev.*, *71*, 231, 1995.

Carr, T.D., M.D. Desch, and J.K. Alexander, Phenomenology of magnetospheric radio emissions, in *Physics of the Jovian Magnetosphere*, edited by A.J. Dessler, p. 226, Cambridge Univ. Press, New York, 1983.

Goldstein, M.L., and J.R. Thieman, The formation of arcs in the dynamic spectra of Jovian decameter bursts, *J. Geophys. Res.*, *86*, 8569, 1981.

Gurnett, D.A., W.S. Kurth, R.R. Shaw, A. Roux, R. Gendrin, C.F. Kennel, F.L. Scarf, and S.D. Shawhan, The Galileo plasma wave investigation, *Space Sci. Rev.*, *60*, 341, 1992.

Gurnett, D.A., W.S. Kurth, J.D. Menietti, and A.M. Persoon, An unusual rotationally modulated attenuation band in the Jovian hectometric radio emission spectrum, *Geophys. Res. Lett.*, *25*, 1841, 1998.

Gurnett, D.A., et al., The Cassini radio and plasma wave investigation, *Space Sci. Rev.*, in press, 2000.

Higgins, C.A., J.L. Green, J.R. Thieman, S.F. Fung, and R.M. Candey, Structure within Jovian hectometric radiation, *J. Geophys. Res.*, *100*, 19,487, 1995.

Higgins, C.A., J.R. Thieman, S.F. Fung, J.L. Green, and R.M. Candey, Jovian dual-sinusoidal HOM lane features observed by Galileo, *Geophys. Res. Lett.*, *26*, 389, 1999.

Kaiser, M.L., M.D. Desch, J.-L. Bougeret, R. Manning, and C.A. Meetre, Observations of man-made radio transmissions by Wind/WAVES, *Geophys. Res. Lett.*, *23*, 1287, 1996.

Ladreiter, H.P., and Y. Leblanc, Modeling of the Jovian hectometric radiation: A three-dimensional study, *Ann. Geophys.*, *8*, 477, 1990a.

Ladreiter, H.P., and Y. Leblanc, Source location of the Jovian hectometric radiation via ray-tracing technique, *J. Geophys. Res.*, *95*, 6423, 1990b.

Ladreiter, H.P., and Y. Leblanc, Low-frequency auroral radio emission from Jupiter: The hectometric radiation, in *Planetary Radio Emissions III*, edited by H.O. Rucker, S.J. Bauer, and M.L. Kaiser, p. 45, Austrian Acad. of Sci. Press, Vienna, 1992.

Ladreiter, H.P., P. Zarka, and A. Lecacheux, Direction finding study of Jovian hectometric and broadband kilometric radio emissions: Evidence for their auroral origins, *Planet. Space Sci.*, *42*, 919, 1994.

Leblanc, Y., On the arc structure of the DAM Jupiter emissions, *J. Geophys. Res.*, *86*, 8546, 1981.

Lecacheux, A., B. Moeller-Pedersen, A.C. Riddle, J.B. Pearce, A. Boischot, and J.W. Warwick, Some spectral characteristics of the hectometric Jovian emission, *J. Geophys. Res.*, *85*, 6877, 1980.

Pearce, J.B., A heuristic model for Jovian decametric arcs, *J. Geophys. Res.*, *86*, 8579, 1981.

Queinnec, J., and P. Zarka, Io-controlled decameter arcs and Io-Jupiter interaction, *J. Geophys. Res.*, *103*, 26,649, 1998.

Reiner, M.J., J. Fainberg, and R.G. Stone, Source characteristics and locations of hectometer radio emissions from the northern hemisphere of Jupiter, *Geophys. Res. Lett.*, *20*, 321, 1993.

Smith, R.A., Models of Jovian decametric radiation, in *Jupiter*, edited by T. Gehrels, p. 1146, Univ. of Ariz. Press, Tucson, 1976.

Staelin, D.H., Character of the Jovian decametric arcs, *J. Geophys. Res.*, *86*, 8581, 1981.

Warwick, J.W., Models for Jupiter's decametric arcs, *J. Geophys. Res.*, *86*, 8585, 1981.

Warwick, J.W., et al., Voyager 1 planetary radio astronomy observations near Jupiter, *Science*, *204*, 995, 1979a.

Warwick, J.W., et al., Planetary radio astronomy observations from Voyager-2 Near Jupiter, *Science*, *206*, 991, 1979b.

Zarka, P., Auroral radio emissions at the outer planets: Observations and theories, *J. Geophys. Res.*, *103*, 20,159, 1998.

Zarka, P., B.P. Ryabov, V.B. Ryabov, R. Prange, M. Abada-Simon, T. Farges, and L. Denis, On the origin of Jovian decameter radio bursts, in *Planetary Radio Emissions IV*, edited by H.O. Rucker, S.J. Bauer, and A. Lecacheux, p. 51, Austrian Acad. of Sci. Press, Vienna, 1997.

D. A. Gurnett, G B. Hospodarsky, and W. S. Kurth, Deptartment of Physics and Astronomy, University of Iowa, Iowa City, IA 52242. (wsk@space.physics uiowa.edu)

M. L. Kaiser, Laboratory for Extraterrestrial Physics, NASA Goddard Space Flight Center, Greenbelt, MD 20771. (kaiser@panacea.gsfc nasa

P. Zarka, DESPA, Observatoire de Paris, 92195 Meudon, France (Philippe Zarka@obspm fr)

(Received November 10, 1999; revised January 4, 2000;
accepted January 4, 2000)