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Discussion Following Roberts' Paper

F. Drake: Although your decimeter rotation period fits the System III period to within $0^s.5$, isn't it now inconsistent with the decameter period, which has recently been changing?

Answer: The decimeter measurements, made 2 years ago, might not disagree with the decameter period observed then if one takes account of the uncertainties involved.

(Paper 69D12–587)

An Interferometric Study of Jupiter at 10 and 21 cm

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An interferometric study of Jupiter's decimeter radio emission has recently been carried out at the Owens Valley Radio Observatory. Using the two 90-ft paraboloids as an interference polarimeter, observations have been made with various east-west spacings ranging from 300 to 4700λ at 10.4 cm and 300 to 2300λ at 21.2 cm and also with some critical north-south spacings at 10.4 cm. Berge and Morris [1964] and Berge [1965] have presented some preliminary results of this study.

Figures 1 and 2 illustrate the east-west interferometer response at 10.4 cm, as a function of baseline, for different orientation combinations of the linearly polarized feed horns. The plotted points are the fringe amplitudes and relative fringe phases respectively. The data are for a 90° range of longitude of the central meridian of Jupiter (System III) centered on $l_{\text{III}}=20°$. The response functions (called visibility functions) vary with l_{III} because of the beaming effect as Jupiter rotates and also because the Jovian source changes its orientation with respect to the interferometer baseline as Jupiter rotates. Both of these effects are a result of the difference of 10° between the directions of the magnetic and rotational axes. It is because of these changes than the data have been segregated roughly according to l_{III}.

At the time of the observations, the position angle measured from north through east in the sky, of Jupiter's rotational axis was 335°. The position angle of the east-west baseline projected onto the sky was always nearly 90°, even at large hour angles.

Moffet [1962] has discussed the theory of visibility functions for unpolarized sources when the feed horns are identical. Morris, Radhakrishnan, and Seielstad [1964] have generalized the results to include nonidentical feeds for studying the polarization distribution over the face of a radio source. The normalized complex visibility function is

$$\beta(s, p)=V(s, p)e^{i\Phi(s, p)}$$

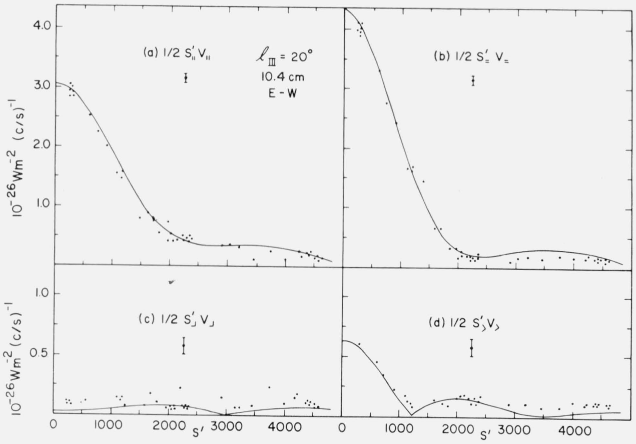

FIGURE 1. *Visibility amplitudes for* $l_{III} = 20°$ *at 10.4 cm (E–W baseline, Oct.–Nov. 1963).*

All scales have been normalized to correspond to a distance for Jupiter of 4.04 A.U. The flux density scale is based on the flux density given by Kellermann [1964] for 3C147 (11.6×10^{-26} Wm^{-2} (c/s)$^{-1}$ at 10.6 cm).

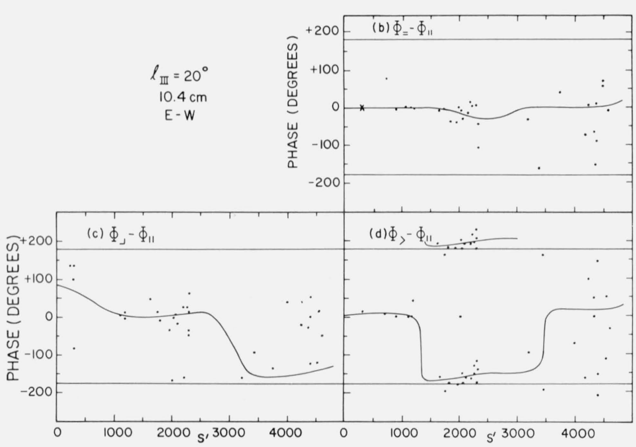

FIGURE 2. *Relative visibility phases for* $l_{III} = 20°$ *at 10.4 cm. (E–W baseline, Oct.–Nov. 1963).*

where

s = Baseline
p = Position angle of baseline
V = Visibility amplitude
Φ = Visibility phase.

Figure 1 gives the unnormalized visibility amplitudes and figure 2 gives the relative visibility phases (there was no absolute phase calibration made) for $p = 90°$. There are similar data for the other three quadrants of l_{III} at 10.4 cm and for all four quadrants at 21.2 cm. There is also some information obtained with the baseline in the direction of the magnetic axis. The meaning of the subscripts shown is as follows: A vertical line represents a feed horn oriented with its electric vector parallel to Jupiter's polar axis, and a horizontal line represents a feed horn oriented with its electric vector perpendicular to Jupiter's polar axis.

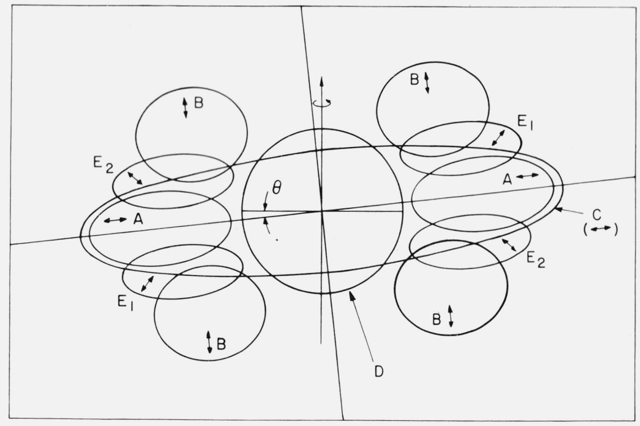

FIGURE 3. *The general model.*

The dimensions are variable parameters. The specific ones shown are similar to the ones determined by fitting.

An initial inspection of the visibility functions indicated that there is a significant thermal contribution from the planetary disk at 10.4 cm, that the nonthermal emission has a very symmetric distribution, and that the polarization properties are roughly what one would expect for synchrotron emission in a dipole magnetic field. To do a more thorough analysis, a model fitting procedure was used. A general model was chosen for the two-dimensional brightness distribution which exhibited features already known or else expected from theoretical and geometrical considerations. This is shown in figure 3. Unknown parameters represent the dimensions, positions and relative contributions of the various regions. All of the regions are taken to be elliptical Gaussians except D which represents the thermal disk contribution. One unknown parameter represents the percentage of linear polarization in each element of the source, and the arrows give the plane of polarization for each.

The model fitting was done by calculating the interferometer response to the model for different values and combinations of the parameters. These calculated visibility functions were then compared with the observed visibility functions to determine the goodness of fit. It was assumed that any intrinsic shortcomings in the general model would show up as serious fitting difficulties. The set of parameter values which provide the best fit yield the model shown in figure 4 for $l_{III} = 20°$ at 10.4 cm. Its calculated response is indicated by the solid curves in figures 1 and 2. The elementary degree of linear polarization is 0.7.

The corresponding model determined for 21.2 cm is very similar. There was much less information available at this wavelength, due mainly to the shorter available baseline. However, it was found that the best fit was obtained simply by taking the position and dimension parameters to be the same as determined at 10.4 cm, taking the disk contribution one-fourth as great, and adjusting the other flux parameters to fit the short baseline results.

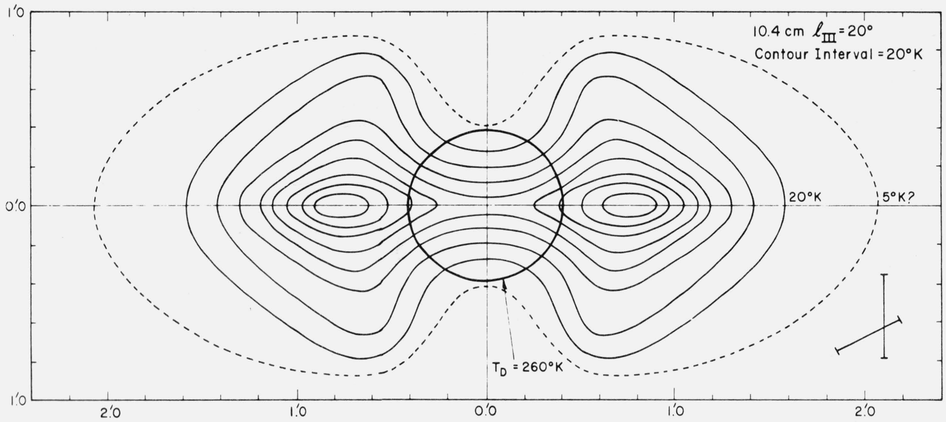

FIGURE 4. *The 10.4 cm brightness distribution determined for* $l_{III} = 20°$.
The scale, in minutes of arc, refers to a distance of 4.04 A.U.

One interesting result is that the disk emission is about twice as high as would be expected for the disk temperature inferred from infrared and 3 cm measurements. It is impossible to fit the parallel horn measurements at 10.4 cm if the emission from the disk corresponds to only 130 °K. In particular, at baselines of 2000 to 2400 λ one gets a well-defined second maximum with a phase reversal for the calculated transforms, and this obviously is not true. The only way to solve the problem is to put much more radiation in the central region. At 21.2 cm, however, this fitting problem was hardly noticeable, and the conclusion was that the extra central emission has a thermal spectrum. Thus it was identified with the thermal disk emission, making a disk temperature of at least 260 °K.

Field [1959] has discussed how the disk temperature produced by the atmosphere may become enhanced towards longer wavelengths in this part of the spectrum. Alternatively, one could have free-free emission in a Jovian ionosphere. However, this would require that the ionosphere be opaque up to 3000 Mc/s and have an electron temperature of only 260 °K.

We might note in passing that the proportion of electrons with steep helices increases as one gets further from the planet. The "polar" emission must arise from far-out electrons which have steep helices.

In general, the distribution of the emission among the various regions and the overall dimensions shown in figure 4 are probably quite accurate. However, the smaller details are not as accurately determined. The available resolution is indicated by the brackets shown in the figure. They represent the separation of a double source, in the direction of the baseline orientation used, whose visibility function would be at its first null at the largest baseline used.

Let us now consider one last result, namely, the detection of a small variable circularly polarized component in Jupiter's decimeter radio emission. If there is a circularly polarized component, an interferometer with parallel, linearly polarized feeds will respond to half of it. The phase of the interference fringes produced will be the same as for the unpolarized and linearly polarized components. With crossed horns the interferometer again responds to half the circularly polarized component, but in this case the phase is different by 90°. It can either lead or lag by 90° depending on the sense of the circular polarization.

Figure 5 shows the data from which the existence of a circularly polarized component was first recognized. The points plotted were obtained during the period 26 January to 3 February 1964, at a wavelength of 21.2 cm and an antenna spacing of 200 ft east-west. They represent the difference in phase between a crossed horn measurement with the *E*-vectors of the horns at 45° on either side of the equatorial direction and a parallel horn measurement. Two different cases are shown, one with horns parallel to the polar axis and the other with the horns parallel to the equator.

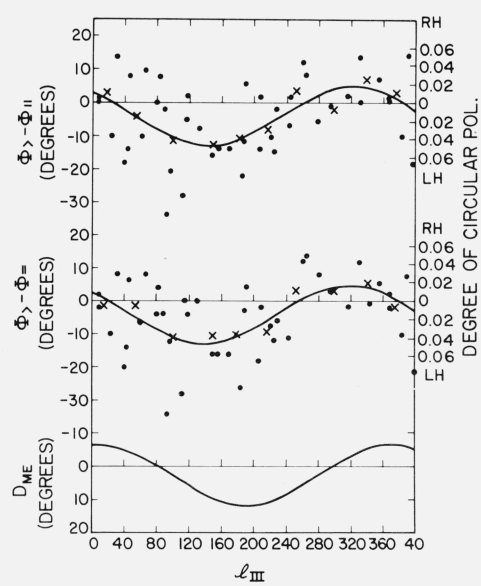

FIGURE 5. *The upper graphs show the evidence for circular polarization at 21.2 cm (200′ E–W, Jan.–Feb. 1964).*
The filled circles are the data points, the *x*'s are means for each 40° of longitude, and the curves are least squares fits of a sinusoid to the data. The lower curve represents the magnetic declination of the Earth.

Both give very nearly the same average and the same variation as a function of l_{III}. The systematic deviation of the phase difference from zero is interpreted as being due to a small variable amount of circularly polarized radiation adding in phase quadrature to the linearly polarized radiation. Similar observations at 10.6 cm made in March 1965, give a similar result except that the amplitude of the variation is only three-fourths as great.

The fact that there is a large periodic variation which is correlated with Jupiter's rotation probably rules out an instrumental effect being responsible for the result. The only other possible explanation of the phase deviation is an intrinsic asymmetry of the source. However, at this baseline, it would be necessary to have an extremely large difference between the centroid positions for the radiation seen with crossed horns and the radiation seen with parallel horns. Also, the fact that the upper two parts of figure 5 give the same result means that the centroid positions for the two parallel horn measurements, only one of which responds to the linearly polarized radiation, are the same. Thus, most of the phase variation must be due to circular polarization. It is true, however, that the base level of the curves can be altered by instrumental effects. From tests made on the instrumental polarization for an unpolarized source, it was found that the maximum amount which the baseline can be shifted corresponds to about ± 0.005 of circular polarization.

This peculiar phase effect is not limited to the short baseline work. If the effect is also attributed to circular polarization for the larger baselines, we can obtain the visibility functions shown in figure 6.

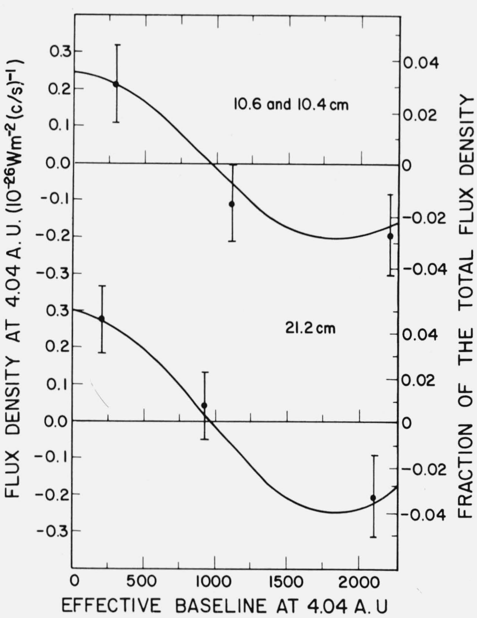

FIGURE 6. *Complex visibility functions for the circularly polarized component at the longitude for which it is maximum.*

The curves, differing only by a scale factor, represent the visibility function of a double source with rather small components.

They represent the circularly polarized component at the longitude for which it is a maximum.

As Dr. Roberts pointed out, Berge and Morris [1964] suggested that the phase effect seen at 10.4 cm for 2200λ was due to a difference in position of the thermal and nonthermal components. However, in view of the fact that it has been seen at 21.2 cm for 2100λ, in which case the thermal contribution is very small, and in view of the new CSIRO position measurements of Jupiter, it seems that the phase effect should be attributed to circular polarization in each case. According to figure 6, the circularly polarized component, when it appears, is a rather well-defined double source with a separation of about 5 equatorial radii. We can conclude that most of it comes from a region near the equatorial plane on each side of the planet.

If we know the place of origin of the circularly polarized radiation, the direction in which the magnetic axis is tipped, and the sense of circular polarization, all at some given longitude, then we can, in principle, determine the direction of Jupiter's magnetic field. In the region of $l_{III} \approx 150°$ or $200°$, the sense is left-handed and the magnetic axis is tipped towards the Earth at the north. The result is that the magnetic pole in the Northern Hemisphere is a north magnetic pole, and the one in the Southern Hemisphere is a south magnetic pole. This is opposite the polarity of the Earth's field, but it agrees with the result inferred by Warwick [1963] from observations of Jupiter's decameter radio emission.

Roberts and Komesaroff [1965] have calculated that for an assembly of monoenergetic electrons in a uniform magnetic field

$$\text{degree of cir. pol.} = \frac{V}{I} = 0.61 \frac{N'(\theta)}{N(\theta)} \frac{mc^2}{E}$$

where θ is the angle between the observation direction and the field direction, $N(\theta)$ is the electron pitch angle distribution evaluated at $\alpha=\theta$, and E is the electron energy. If the observation frequency is at the frequency of maximum emission for the electrons ($\nu=\nu_c/3$) and if we use the relation between the critical frequency, field strength and electron energy, we get

$$\text{degree of cir. pol.} = 0.72 \frac{N'(\theta)}{N(\theta)} \left(\frac{B_0 \sin \theta}{\nu}\right)^{1/2}$$

where B_0 is in Gauss and ν is in Mc/s. Let us make the assumption that in the two regions where the circularly polarized radiation originates the magnetic field is parallel to the magnetic axis. When the magnetic declination of the Earth is 0°, then $\theta=90°$ and we know that

$$N'(90°)/N(90°) = 0.$$

However, when the magnetic declination of the Earth is maximum, $N'(\theta)/N(\theta)$ should be quite large (let's say 5) because the distribution of helix angles is sharply peaked at $\alpha=90°$. Qualitatively we would then ex-

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pect the result shown in figure 5. If we say that the maximum degree of circular polarization is 0.1 in the regions where it originates, then we find that $B_0 \approx 1$ G and $E \approx 15$ Mev in these regions. The uncertainties are quite large, but we see that by making reasonable assumptions we have obtained numbers which agree with those suggested by Chang and Davis [1962] from other considerations of the decimeter radiation.

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(Paper 69D12–588)

Discussion Following G. L. Berge's Paper

A. Barrett: Describe the spectrum of the disk component.

Berge: At 10 cm the disk temperature for this component must be quite close to 260 °K. At 21 cm it is poorly determined (260 °K with an uncertainty of perhaps ±50%), but obviously the spectrum is more like a thermal spectrum than a flat spectrum (which would give about 1000 °K, at 21 cm if it is 260 °K, at 10 cm).

C. Sagan: In view of the large number of unknowns regarding Jupiter's atmosphere, the high temperature for the disk at 10 cm might not be unreasonable. It would be interesting to fit models which would yield this property.

C. Sagan: Could you determine whether there is limb darkening for the disk?

Berge: That is impossible with the present data. The fitting procedure assumed a uniform disk, and only a severe departure from this assumption could have been detected.

K. Kellermann: How do the visibility functions change with the longitude of the central meridian?

Berge: The beaming is apparent of course, but unfortunately it is difficult to say much more about it than what we know from single-dish work. The effect produced by having the source change its orientation with respect to the baseline as Jupiter rotates is also very evident.

K. Kellermann: What is the distribution of polarization across the source?

Berge: The plane of polarization for each element of the source was indicated in the figure showing the general model. The degree of linear polarization for each element (except the disk) seems to be about 0.7.

S. Silver: How good was the polarization discrimination between horns? Were they isolated from each other?

Berge: The discrimination was good. The horns were isolated in that there was one on each dish. On an unpolarized source the "crossed horn" combination yielded a fringe amplitude of, at most, 0.5 percent of the "parallel horn" combination.

J. Roberts: Have you tried to determine something about the pitch angle distribution from your work?

Berge: No, not quantitatively.