At periods when the bursts are similar at the two ends of the baseline, the fringes are stable over periods of several minutes. In a typical example, the 42 fringes recorded over a period of several minutes indicated a systematic movement of less than 4 sec of arc, and a maximum scatter of ±3 sec of arc. Thus neither the size of the region in which successive bursts occurred, nor its systematic movement, exceeded 0.1 of the planetary diameter.

Observations of the increase in the angular size of other radio sources seen through the ecliptic suggest that interplanetary scattering can explain the observed angular sizes of the Jupiter bursts, and that the intrinsic size of the bursts is less than the apparent size. It is suggested that the scattering regions are 0.01 to 4.2 A.U. from the Earth. It is furthermore suggested that the apparent burst structure of the Jovian radiation is produced by scintillations occurring within 0.01 A.U. of the Earth.

Note added in proof: The authors now consider that the restriction of the electron irregularities responsible for the scintillations to a region within 0.01 A.U. of the Earth is probably not correct on account of focusing difficulties. In all probability, the observed angular sizes and the burstiness of the radiation are manifestations of a random diffraction process occurring between the Earth and Jupiter, although it is not certain that the same electron irregularities are responsible for both effects.

References

Bigg, E. K. (1964), Influence of the satellite Io on the Jupiter's decametric emission, Nature **203**, No. 4949, 1008–1010.

Slee, O. B., and Higgins, C. S. (1963), Long baseline interferometry of Jovian decametric radio bursts, Nature **197**, 781–782.

Discussion Following Slee and Higgins' Paper

Frank Drake: J. N. Douglas has recently shown that the direction of drifts observed over several stations reverses at times of Jupiter opposition. This reversal is consistent with the sources of the scintillations moving along with the solar wind outward from the Sun. The inferred scale of structures is hundreds of kilometers, and the speeds are upwards of 1000 km/sec. This picture is consistent with our picture of interplanetary scintillations observed in small radio sources by Hewish.

(69D12–585)

Frequency and Polarization Structure of Jupiter's Decametric Emission on a 10-Millisecond Scale

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and

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We present observations of decameter Jupiter emission on a 10-millisecond time base. After describing the swept-frequency polarimeter we discuss polarization and spectral characteristics in terms of propagation conditions along the ray path from Jupiter to Arecibo.

Formidable evidence has accumulated during the 10 years of Jupiter decametric observations on the existence and reality of exceedingly short-lived and narrowband phenomena. On time scales from no longer than a few seconds down to a few milliseconds, these structures have been seen with a variety of different techniques, from dynamic spectrographs, through multistation equipment, to wide-baseline interferometers. The major question that has been asked has been the source of the fluctuations: Is it in the terrestrial ionosphere, in interplanetary space, or in or near the source of the radiation at Jupiter itself? The answer given generally has been that the interplanetary medium is responsible, the data thus suggesting fine structure in the solar wind plasma flowing out from the Sun. In fact some of the data (such as time shifts observed between data from multiple stations) support this conclusion, but others do not (for example, failure of correlation at closely spaced stations, and some of the structures on dynamic spectra).

With these problems in mind we decided to investigate the fast-time evolution of the spectrum with as complete a determination of the state of polarization of the waves as we could establish. We were fortunate to be able to use the Arecibo 1000-ft dish for this work, with a broadband, crossed-polarization, log-periodic dipole feed designed by Collins Radio Company for the Air Force Cambridge Research Laboratories. With this combination, Jupiter's decametric emission could be probed over a wide frequency range, with high speed, and satisfactory polarimetry.

A suitable receiver did not exist, and in fact, since we considered that the polarization objectives were very important, we had to invent one for the task.

We had found that terrestrial Faraday effect was a common aspect of our more limited data taken in Boulder with the slow dynamic spectrograph (see fig. 1). The existence of this well-established effect suggested the format for our eventual Arecibo receiver. In the Earth's ionosphere, even at subequatorial latitudes such as that of Puerto Rico, at 30 Mc/s the propagation modes are quasi-longitudinal over a wide range of θ. Since the terrestrial Faraday effect results from the differential phase path developed between the ordinary and extraordinary modes (which have opposite circular polarization), by observing Jupiter in these modes we can eliminate the effects of our ionosphere. A polarimeter that determines only two intensities cannot establish the complete EM state of the incoming waves. It is necessary by some means to measure the phase difference between the circular modes as well. Furthermore, the intensity of the waves that are uncorrelated between the two circular modes must be established so that we can measure any *un*polarized component of the incident radiation.

We have combined these various functions into a single spectrographic receiver in the following way. If we combined the outputs of the two circular antennas, the resultant signal would represent the signal received by a single linear dipole. The position angle of the dipole is determined by the phase difference between the ordinary and extraordinary mode antennas. We actually combine the O and E modes through a 100-m length of coaxial cable. Therefore, as a function of frequency, the phase difference between O and E changes linearly in an easily predicted way. The combined O and E signal therefore represents what would be seen by a spatially rotating dipole making about four complete revolutions as our receiver sweeps from 24 to 36 Mc/s. A compromise is, of course, involved, in that we do not observe the complete state of polarization at *all* frequencies in this range. We must assume that the polarization is constant over approximately 2 Mc/s of the swept range (the fringe separation as a function of frequency). As an alternative to assuming constancy of the polarization, we might assume that we know the mechanism that causes the polarization to vary. For example, it might be terrestrial Faraday effect. We might then use this effect to predict what the records should look like. The point is that we do not necessarily need to know the polarization at intervals as close as 2 Mc/s or less in order to determine completely the state of the incoming radiation.

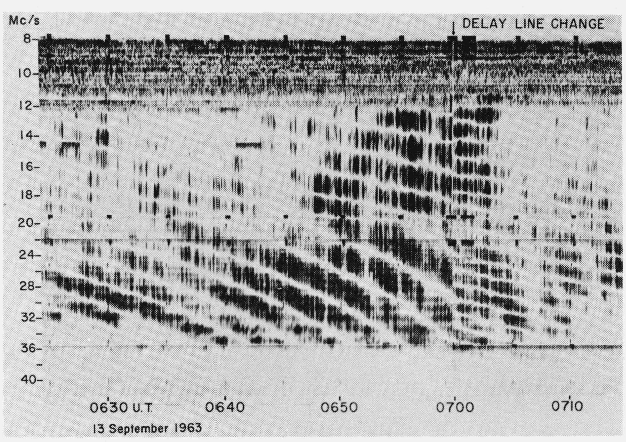

FIGURE 1. *Faraday effect in Jupiter's decametric emission (Warwick and Dulk, 1964)*[1].
The Faraday fringes are nearly horizontal dark streaks which are widely spaced in frequency at high frequency, 36 Mc/s, but become closely spaced towards 20 Mc/s. The curved diagonal white streaks are interferometer fringes, whose origin is purely instrumental.

Our receiver operates on a time-shared basis between the following configurations: (a) combined (rotating linear dipole); (b) left circular; (c) right circular. The sequence is (a), (b), (a), (c), (a), etc., with each sweep in a given mode requiring 10 msec to complete.

The presentation is on 35-mm film, with the two circular states together occupying about half the width of the film, and the rotating linear display on the other half. There are separate oscilloscopes for each of the two halves, and they are simultaneously photographed on a continuously moving film. With an upper limit of only 0.04 sec for events to be completely resolved in time we are able to record Tau A as a control for sensitivity and standing-wave ratio. In fact, the radio star produces a perfectly smooth broadband record, just as we would expect if our equipment operates properly. This confirms the measurements we have been able to carry out of its performance by laboratory studies of the quadrature hybrid combiner, and field studies (made from the "vertex" of the 1000-ft dish) of the cross-polarization response of the Collins log-periodic feed. The isolation between the crossed elements exceeds 25 dB.

In virtually all the data we recorded, with but very few exceptions, our equipment did not impose any limitations resulting from the time between sweeps. Out of 19 recorded Jupiter events, taken on a total of 37 nights of observations in October, November, and December 1964, we had only three cases of bursts faster than the 0.04-sec sweep repetition rate. We shall return to the most important of these in a moment.

First of all, however, we will exhibit data typical of the great majority of our observations. Figure 2 shows the linear dipole record at the top, above the two narrower strips from the circular antennas. The middle record is the left-circular state. Note the relative separateness of the individual sweeps from the circular antennas, a result, of course, of the programming of the sweeps.

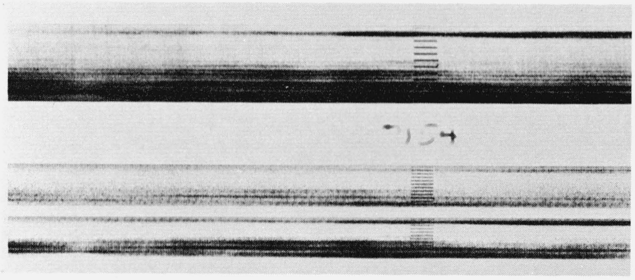

FIGURE 2. *Arecibo swept-frequency polarimeter record at 0154 UT, 10 December 1964.*
Each of the three strips covers the range 24 to 37 Mc/s. The total length of the record is about 15 sec (see text for further description).

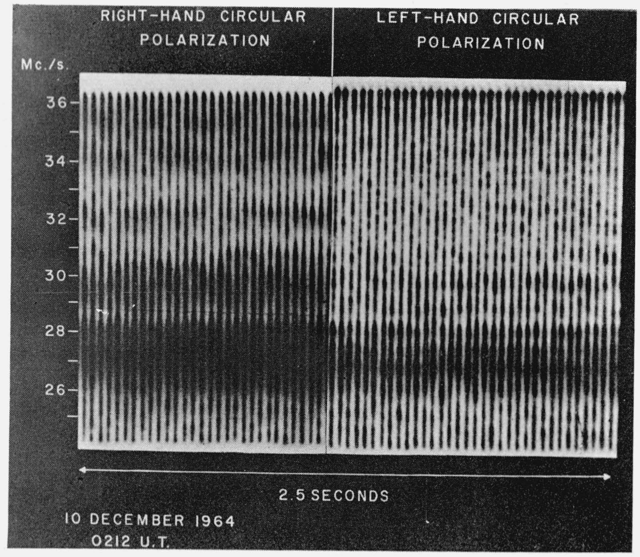

FIGURE 3. *A detail of the record from 0212 UT, 10 December 1964.*
Immediately adjacent records in the L and R states are compared (see text).

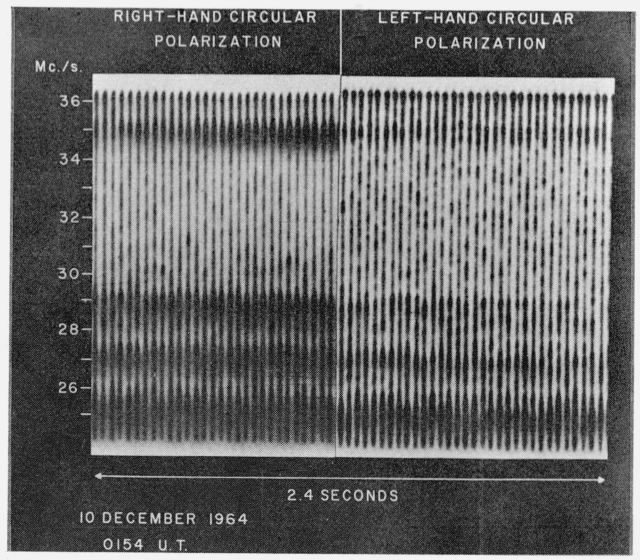

FIGURE 4. *Same as figure 3, but at 0154 UT (see text).*

This equipment also ran, at much wider bandwidth, on simple dipoles against a ground screen in Boulder. Even on those poorer records the phenomena of this event were clearly visible: slow variations in the intensity, and complex structure in frequency. Especially, note the narrow-bandwidth, high-frequency strip of isolated emission. We should mention in particular that for almost all of these records from Arecibo we have matching records made in Boulder; the identification of these bursts as Jupiter bursts is therefore virtually certain in all cases.

Because we have, in effect, a rotating linear antenna, we can by appropriate choice and location of the delay line in a circular channel, speed up or slow down the Faraday rotation of an eventually fixed polarization ellipse in the record. On the linear strip, one can see the Faraday fringes clearly. Note, for example, their variation in frequency; they are spaced more closely at 24 Mc/s than at 30 Mc/s. As we had already concluded from the Boulder records of this phenomenon on other occasions, this kind of record is in general completely consistent with the assumption that all of the Faraday effect occurs in the Earth's ionosphere, which is a puzzling conclusion in view of the facts of Jupiter's strong magnetic field and ionosphere.

The two circular states also show strong and variable structure independent of the Faraday effect shown on the linear record. Note, however, that the structure of the circular polarization does appear as modulation on the linear channel. The right-hand signal is consistently stronger than the left-hand, which confirms and extends to high frequency the earlier determinations of the ellipticity and sense of the decametric emission.

Figures 3 and 4 show a detailed comparison of the structure in frequency in the circular states. Despite the complication of the structure, it is in fact identical on the two channels, L and R. The emission therefore is elliptical with roughly constant axial ratio and orientation as a function of frequency above 24 Mc/s. This result is consistent with the previous Boulder result. The striking periodicity in frequency suggests a standing-wave effect, perhaps a combination of direct and reflected waves from Jupiter or perhaps elliptical Faraday effect. The effect most likely occurs at Jupiter.

We found an especially persistent case of extremely fast variations on 17 October 1964. Figure 5 shows this event as it appeared in Boulder. Note the sharp high-frequency cutoff above 28 Mc/s, and the narrowband emission at this frequency. Figure 6 shows the early phase of the event at Arecibo, when a steady source appeared together with very rapid variations. Later on, this event had only rapid variations, but we believe that the combination of this early *steady* source alongside bursts with high-speed modulation, demonstrates that the fast bursts originate in or near Jupiter.

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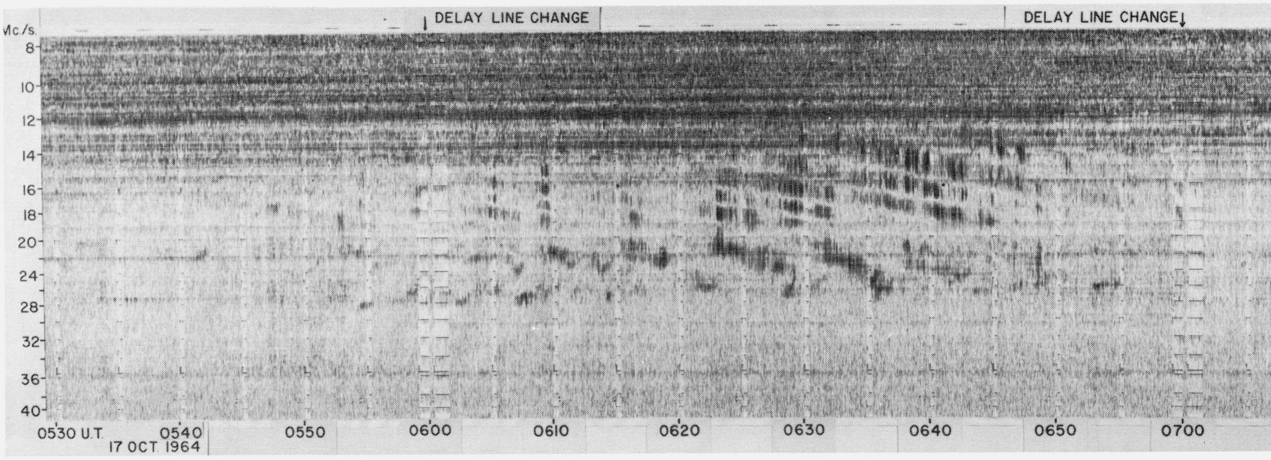

FIGURE 5. *Boulder spectrogram of Jupiter emission on 17 October 1964 (see text).*

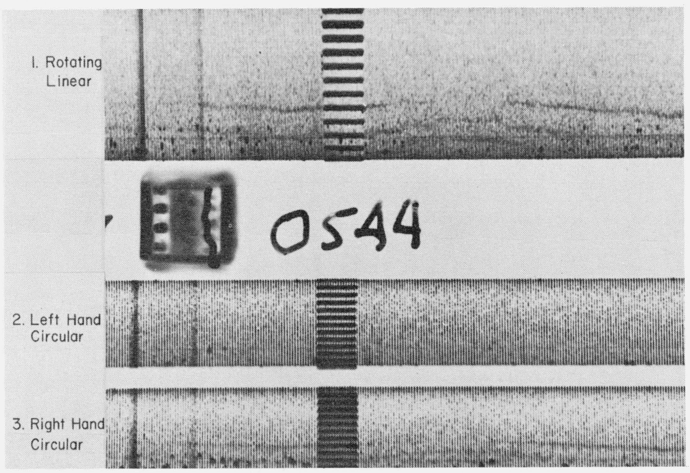

FIGURE 6. *Arecibo record near 0544 UT, 17 October 1964.*
Note the narrowband, but smooth emissions in the form of lanes or paths. These are right-elliptically or circularly polarized, as are indeed the remaining fast bursts that appear on this record.

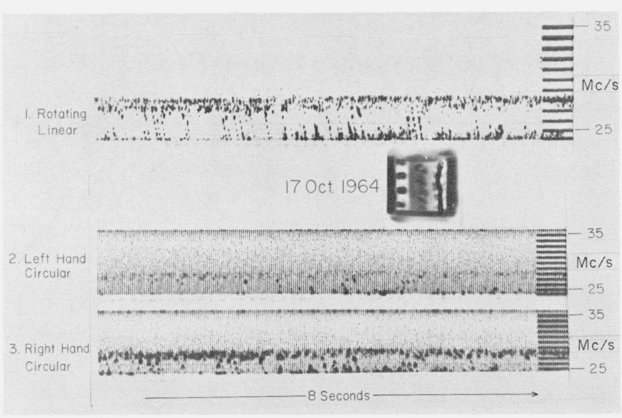

FIGURE 7. *0544 UT, 17 October 1964.*
Fast bursts, drifting at 25 Mc/s², appear alternately on all three traces (see text).

The propagation path from Jupiter to us must be virtually identical for the two kinds of emission. Only at the source itself could such a difference arise.

Figure 7 shows the same event a few minutes later, when there are only high-speed fluctuations, and no steady source.

Figure 8 illustrates the way in which the high-speed burst appears alternately on successive spectral scans in the different polarization modes. Half as many pips appear on the L and R channels as a result of the time-sharing scheme. [Note that the burst of figure 7 appear many more times (8 or 10 on L + R) than does the idealized drifting burst of our sketch.] A very strong burst that persists during the three sweeps would likely appear, regardless of polarization, on all three channels. Therefore, it is difficult for us to make a detailed statement about the nature of the polarization variations in just one isolated burst. The frequency-drift rate is another matter; it is in the sense from high to low frequencies, and amounts to 5 to 35 Mc/s^2. The bursts obviously occur over and over again with very similar drift rates.

We *can*, however, speak of the polarization variations in frequency because of the statistical properties of the bursts. Figure 9 shows the 17 October events a few minutes later, when the occurrence of bursts seems to aline the pips, especially on the combined channel. This strongly implies that the polarization of the bursts varies with frequency in a way that is stable in time for, at first, only a few seconds, but then, in later minutes of the event, long periods of time involving literally hundreds or thousands of bursts. We conclude, in other words, that the bursts are strong at a given frequency because the polarization ellipse is parallel to our dipole at that frequency, and *not* because our receiver happened to be tuned to the particular frequency of the burst at that exact moment. To repeat, the alternatives are that the time of beginning of each burst would have to be correlated with the sweep of the receiver *or* the burst polarization varies in a consistent way with frequency, but remains almost constant in time.

The L channel is weaker than the R channel, in general but not in detail, as can be seen, for example, in figure 10. In fact, when one looks at this record in order to compare the frequencies at which the pips occur, one finds that they are anticorrelated between L and R (figs. 10 and 11). One cause of such an effect might be the speed with which the bursts flick across our range (mentioned above), which might imply an alternation between L and R. The difficulty with this explanation is that the bursts line up, clearly on L + R, and also probably on L and R separately.

The peaks of the structure are strongest on the R record; at the time of a burst on the L record, however, the burst is stronger there than the emission simultaneously appearing on the R record. An average over a few tenths of a second of this kind of record would therefore resemble fixed-frequency polarimetric

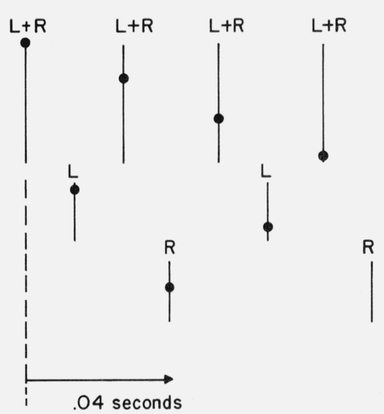

FIGURE 8. *Illustration of the way in which the high-speed burst appears alternately on successive spectral scans in the different polarization modes.*

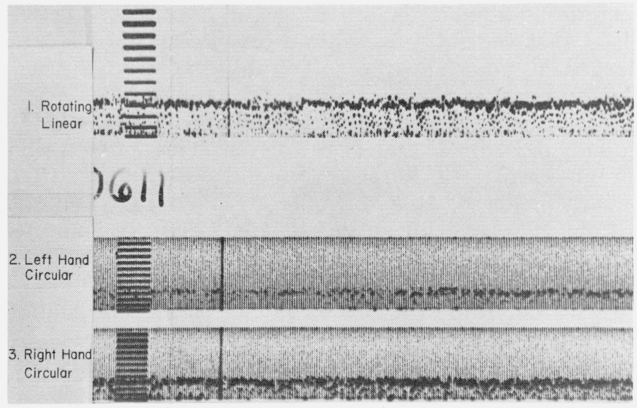

FIGURE 9. *0611 UT, 17 October 1964.*
Fast bursts, with quite similar drift rates, occur in alined patterns on the rotating linear trace (see text).

[1] Warwick, J., and G. Dulk (1964), Faraday rotation on decametric radio emissions from Jupiter, Science **145**, 380–383.

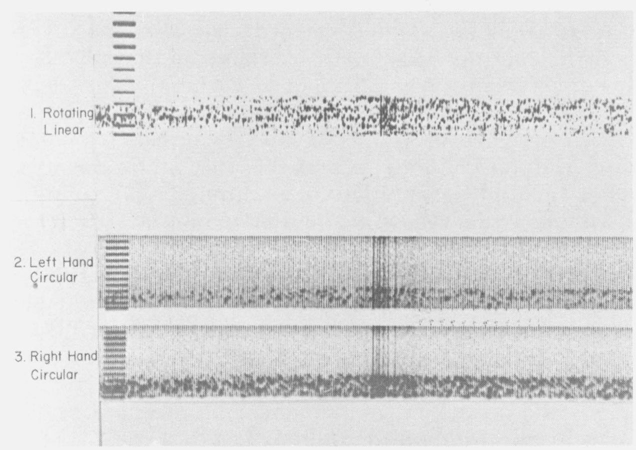

FIGURE 10. *0615 UT, 17 October 1964.*
Fast bursts, showing alinements as in figure 8; the burst patterns on the L and R traces are anticorrelated (see text, and fig. 10).

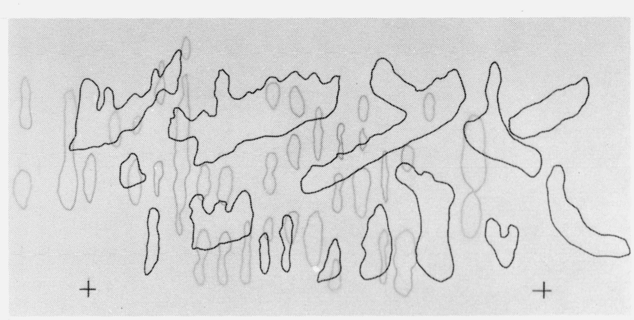

FIGURE 11. *0615 UT, 17 October 1964.*
A very much enlarged portion of the L and R traces, which have been superimposed. The R trace is the heavy lines, the L, the lighter ones.

records as already described in the literature. Note, also, that mixed polarization events as previously described could also result from this kind of fine structure in time and frequency.

It seems probable that the anticorrelation of frequency-periodic L and R in this case indicates a different species of Faraday effect from the one that occurs in the Earth's ionosphere. The Jupiter effect distorts a wave with an initial polarization in an elliptical mode into a wave whose polarization sense, axial ratio, and orientation vary periodically with frequency. For this effect to take place the base states describing modal propagation at Jupiter should be orthogonal elliptical modes. Because the L–R polarization balance favors R, we can conclude that the base modes are *elliptical* (albeit with large axial ratio) rather than linear. If we measure all parameters of the L and R records we can in principle determine the polarization of the wave that initiates the Faraday effect, and the direction of propagation with respect to the magnetic field.

Figures 6, 7, 9, and 10 show successive phases in the development of Jupiter emission on 17 October 1964. The progression, from clearly separate bursts to swarms of nearly overlapping bursts, suggests that we consider seriously whether Jupiter emission consists of a superposition of myriads of such microbursts. Despite such a record, we also, however, have to confront data such as those at the outset of this day's record, when little or no variation in intensity was to be seen in one component of the emission.

Two or more mechanisms may be present, or perhaps the microbursts represent only a propagation effect, a kind of scintillation in Jupiter's ionosphere. If we follow that reasoning for a moment, the structures might represent wedges or waves in Jupiter's atmosphere. The angular distance through which Jupiter rotates over the duration of a burst would correspond to fine structure in the angular emission pattern from a coherently excited source region on Jupiter. According to this description, the "burst" is in reality emission into a kind of antenna lobe swept past the earth by the rotation of Jupiter.

Jupiter rotates about 0.04 sec of arc per millisecond of time. Suppose a coherently excited source region was big enough (on rare occasions) to extend over a large enough distance that could produce an angular fine structure corresponding to 0.04 sec of arc. There are 2×10^5 sec of arc per radian, so that 0.04 sec of arc implies a distance of $2 \times 10^5/0.04 = 5 \times 10^6$ wavelengths. At 30 Mc/s, this distance is 50,000 km, a substantial fraction of 1 Jupiter radius (=71,000 km). What we must conclude is that coherent excitation of the emission would have to take place over areas nearly as large as the visible surface of the planet! This may already defeat such a proposal; a shattering defeat would have required a coherence distance larger than the planet. If there were fine structure much shorter than 1 msec it would rule out the mechanism. However, from our data taken at their face value, the region of coherence might be as small as only 5,000 km (10-msec bursts).

Actually, that planetary-scale phenomena might be involved appears to us as an *attractive* feature. We note, for example, the tiny size of the satellite Io, yet its longitudinally wide range of influence on the decametric emission. Launched from regions perhaps only a few kilometers in dimension, particles stimulated by Io project through over 400,000 km of converging lines of force into Jupiter's ionosphere, and these affect a wide range of longitudes.

Discussion Following Warwick and Gordon's Paper

I. Shapiro: What is the strongest evidence for a magenetic field on Jupiter?

Answer: The consistent right-hand polarization of the low-frequency emission, and the substantial angular extent of the decimetric emission.

J. A. Roberts: Slee suggests that the fast variations are imposed in the space between Jupiter and the Earth. How can the mechanism you propose be consistent with his result?

Answer: We have only seen these fast bursts rarely, and there may be more than one mechanism producing this kind of modulation. Our evidence was that simultaneously fast and slow variations appeared in the Jupiter data on 17 October 1964.

(69D12–586)