RECENT RADIO OBSERVATIONS OF JUPITER

Max M. Komesaroff
University of Maryland
College Park, Maryland

I. Introduction

During the ten years that have elapsed since it was discovered that Jupiter has unexpected properties when observed at radio frequencies, a considerable amount of observational data has accumulated. In describing some of the more recent results, it is convenient to discuss the observations below 40 Mc/sec separately from those made above about 200 Mc/sec, since the characteristics of the radiation in the two frequency ranges are markedly different.

In the decameter wavelength range the radiation is sporadic, elliptically polarized, and frequently extremely intense. At any one time the radiation source is considerably smaller in angular size than the planetary disk. By contrast, from about 200 Mc/sec to several thousand megacycles, the nonthermal intensity component is steady and amounts to only a few flux units. The predominant polarization is linear, and the radio source is several times more extended than the planet. The high-frequency radiation is thought to be fairly well understood, but this is not so for the decameter bursts.

II. The Decameter Radiation

A. Time Variations

1. Dependence on System III longitude. Soon after Burke and Franklin (1955) discovered the decameter radiation, their discovery was confirmed by Shain (1955 and 1956). Using records going back to 1951, Shain was also able to demonstrate a periodicity in the Jovian emission only some seconds shorter than the optically determined System II period, which corresponds to the observed movement of clouds in the nonequatorial belts of Jupiter. Carr et al. (1961) and Douglas (1960) have used data extending over nine years to derive a more accurate period, and their estimates differ from one another by only 0.02 sec. Commission 40 of the International Astronomical Union (IAU) has recommended the use of System III longitudes for the presentation of Jovian data. This system has a rotational period of $9^h55^m29^s.37$ and coincides with System II at 0^h UT on January 1, 1957. Observations of the Jovian microwave source have indicated that it, too, rotates with the System III period, which is taken to be the rotation period of the planetary magnetic field.

Figure 1 shows the frequency of occurrence of Jupiter activity as a function of λ_{III} for several frequencies. It is due to Smith et al. (1965), and indicates that near 20 Mc/sec the greatest probability of Jupiter's radiation occurs when the longitude range 220° to 260° is presented towards the Earth. Subsidiary peaks occur for $\lambda_{III} \simeq 130°$ and $\lambda_{III} \simeq 330°$. The three peaks on this histogram will be subsequently referred to as the "main peak," the "early peak," and the "late peak."

Figure 2, also due to Smith et al. (1965), shows the System III longitude of the main peak at 18.0 Mc/sec since 1952. It would seem to indicate that in early 1960 a substantial change occurred in the rotation rate.

2. *Short-period fluctuations.* On a much shorter time scale, fluctuations are observed whose durations vary from several milliseconds (Kraus, 1956; Douglas and Smith, 1961) to some minutes. More usually the durations are between a few tenths of seconds and several seconds.

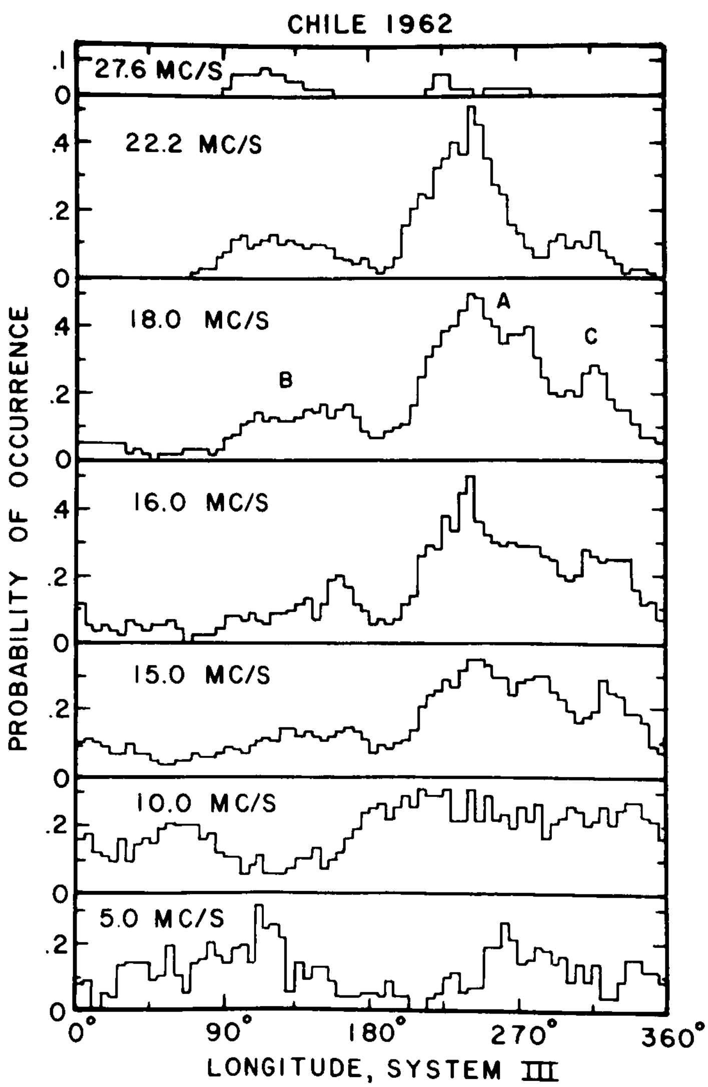

Fig. 1. Histograms of probability vs System III (1957.0) longitude for the 1962 observations made in Chile (Smith et al., 1965). (From *The Astrophysical Journal*, 1965, Vol. 141, p. 463)

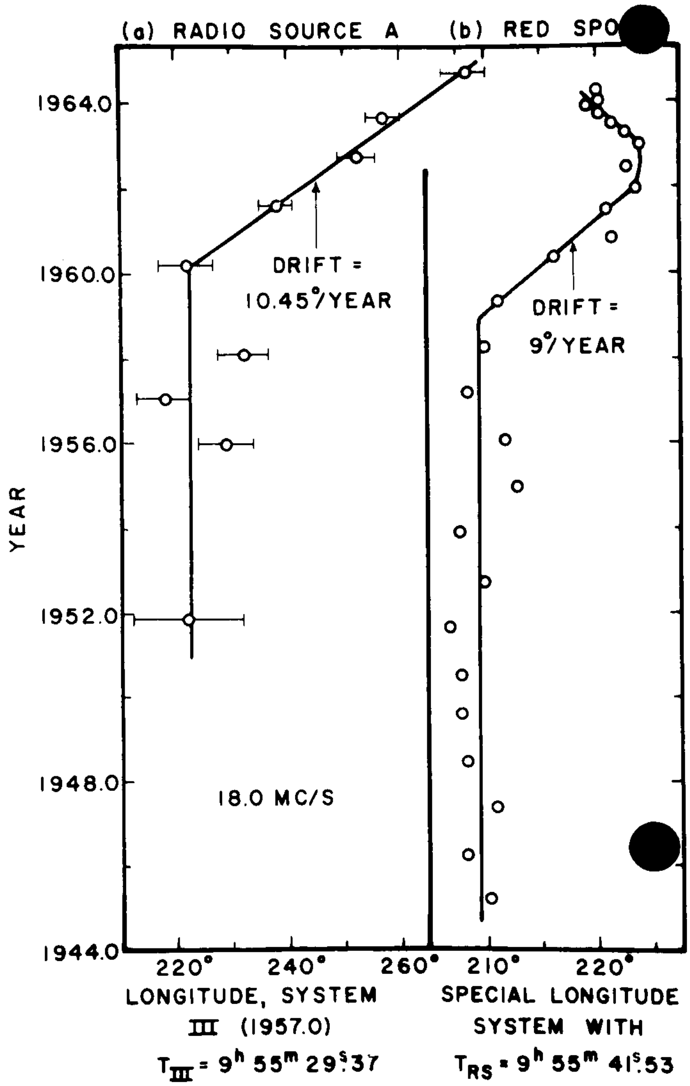

Fig. 2. (*a*) Drift of main source in System III (1957.0) coordinates; (*b*) drift of the Great Red Spot in a special longitude system designed to minimize its motion from 1945 to 1959 (Smith et al., 1965). (From *The Astrophysical Journal*, 1965, Vol. 141, p. 471)

Simultaneous observations at different observing sites (Gardner and Shain, 1958; Douglas and Smith, 1961; Smith et al., 1960) have indicated that some of this structure is imposed by the terrestrial ionosphere. However, the results of Douglas and Smith (1961) indicate that the radiation contains at least some of the burst structure when it impinges on the ionosphere.

Recent observations reported by Smith and Douglas (1962) and Douglas (1964) indicate that many of the bursts may represent an effect due to the interplanetary medium. At times when there was good general correlation between the burst structure recorded at separate sites, they found a consistent relative delay in the arrival time of the bursts at the two sites. Furthermore, they found that the sense of this delay reversed near opposition. Their interpretation is that pulses of duration of about one second are produced by diffraction in interplanetary electron clouds. Near opposition the clouds' component of drift velocity perpendicular to the Earth–Jupiter line might be expected to reverse.

B. Source Size Measurements

The evidence for interplanetary scintillations implies a small angular diameter for the source. Slee and Higgins (1963) have made source size measurements using a wide-based radio link interferometer. The most recent set of observations, reported by J. A. Roberts at the Arecibo Symposium on Planetary Atmospheres and Surfaces, was made with a base line of 12,700 λ. They found that the apparent source size varied between 5 and 15 seconds of arc.

C. Spectral Characteristics

Referring again to Fig. 1, we see that the main peak of emission, which is very pronounced near 20 Mc/sec, decreases at the lower frequencies, and that at 5 Mc/sec there are two peaks of roughly equal amplitude separated by about 180° in longitude. Similar results have been obtained by McCulloch and Ellis (as reported by Ellis at the Arecibo Symposium). Ellis has shown that if the quantity plotted is mean power rather than occurrence probability, the histograms are similar, except that the peaks are more pronounced.

Detailed spectral studies have been made by Warwick (1961, 1963) using a dynamic spectrum analyzer. His records show that at any one time the Jupiter radiation may extend over a frequency bandwidth as wide as 20 Mc/sec, and that within this band short-lived features can be discerned (presumably corresponding to the "bursts" seen on single-frequency records), usually extending over only a few megacycles.

Warwick found that the whole band of activity may drift with time toward higher or lower frequencies and that this drift depends on the central meridian longitude. For longitudes above 200° the drift is toward lower frequencies, whereas for $\lambda_{III} \simeq 140°$ the drift is in the opposite sense. Warwick (1963) found that individual spectral features (or "landmarks") tend to recur at the same longitudes, so that records taken on different days can be superimposed on the basis of these "landmarks" to yield surprisingly good coincidence in their longitude scales. Figure 3 shows the longitudes of radio "landmarks" plotted as a function of time from opposition

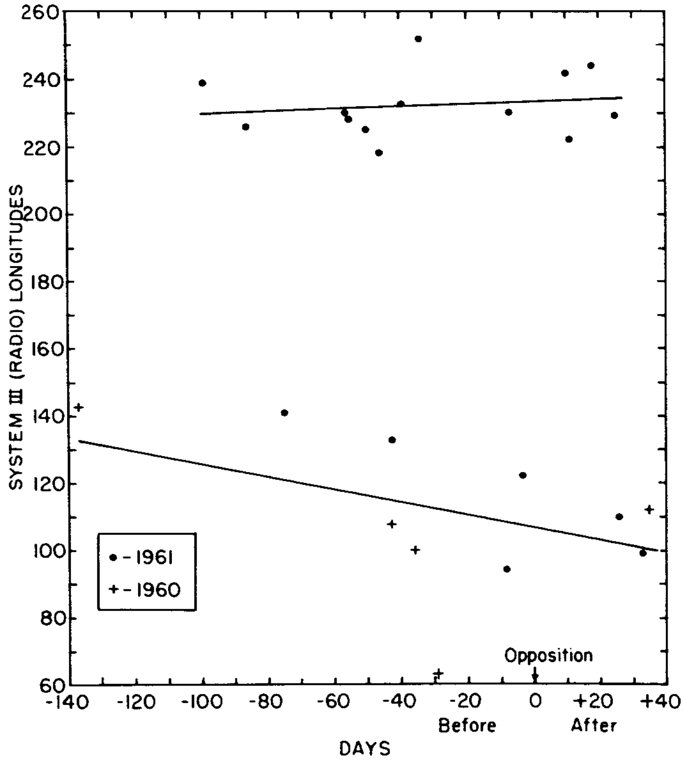

Fig. 3. Relation between λ_{III} (1957.0) longitudes of radio special landmarks and time in days from opposition. Only 1961 data enter the relation for negative-drift emission, the upper of the two groups of points. The negative drifts define a horizontal line within the precision of measurement, while the positive drifts define a line of decreasing longitude as time increases during the apparition (Warwick, 1963). (From *The Astrophysical Journal*, 1963, Vol. 137, p. 45)

for data taken in 1961 and 1962. It illustrates two interesting facts:

1. The scatter of points about the least-squares lines shows that the radiation is sharply beamed into a cone of half angle only about 9°.
2. Whereas features in the main peak ($\lambda_{III} \simeq 230°$) remain essentially fixed in longitude, those in the early peak drift toward lower longitudes through the time of opposition.

Point 2 presumably explains the broadness of the early peak as shown in Fig. 1. It should be noted that the sense of the drift in longitude is opposite to what would be expected if the radiation were stimulated by solar radiation as suggested by Shain (1956).

Warwick (1963) has pointed out that the stability of the spectra evidently rules out an explanation of the spectral features in terms of plasma frequencies in an assumed Jovian ionosphere. Such an explanation would imply that Jupiter's ionosphere is vastly more stable than the Earth's. Thus, current theories (Ellis and McCulloch, 1963; Ellis, 1965; Warwick, 1961, 1963) have related the frequencies of emission to the gyrofrequencies of electrons streaming along the Jovian magnetic field lines.

D. Polarization

Observations showing a high degree of circular or elliptical polarization support the idea that magnetic fields are intimately connected with the radiation process. Above about 20 Mc/sec, the sense of rotation is almost exclusively right-handed circular. This is true whether the measurements are made in the northern or southern hemisphere, indicating that the polarization is not imposed by the terrestrial ionosphere. Franklin and Burke (1958) found some 22 Mc/sec bursts associated with the early longitude source that had the left-handed sense of rotation. Barrow (1962, 1963) and Sherrill and Castles (1963) found an increasing proportion of left-handed bursts below 20 Mc/sec. At 10 Mc/sec, Dowden ([illegible]3) recorded both senses, the right-handed sense being associated with the main peak and the left-handed predominantly with the early peak.

E. Solar Correlations

There have been several reports (Kraus, 1958; Carr et al., 1960; Warwick, 1963) suggesting a positive correlation of Jupiter emission with solar activity occurring some days previously. However, there is some conflict between conclusions drawn by the various observers, and it seems

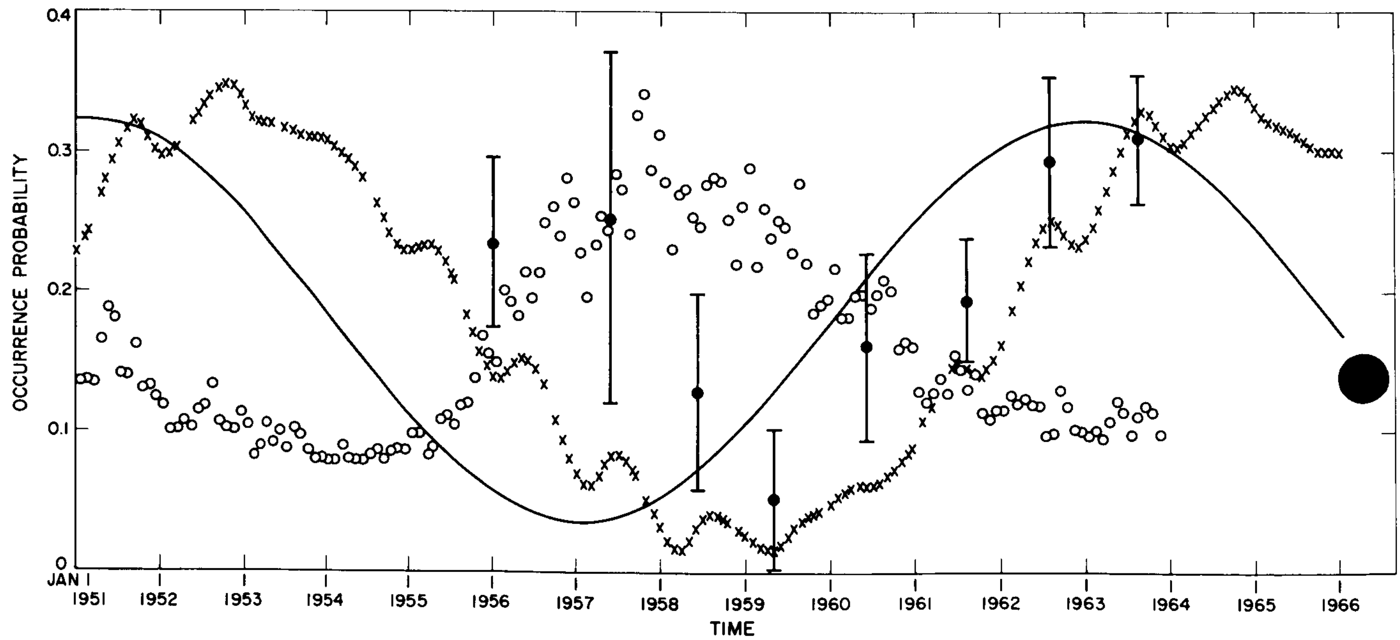

Fig. 4. 22.2-Mc/sec main source occurrence probability (heavy dots with error flags) compared with provisional sunspot number (open circles). Also shown (without ordinate scales) are declination of Earth seen from Jupiter (x's) and sub-Jovian latitude on the Sun (line). Range of sub-Jovian latitude on the Sun is about ±9°; range of declination of Earth is about ±3° (Douglas, 1964).

that insufficiency of data prevents firm conclusions being drawn.

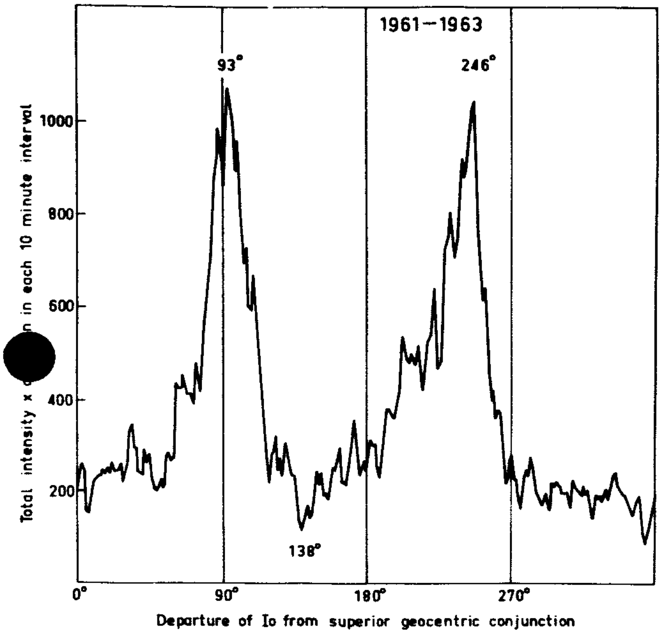

Fig. 5. Dependence of Jupiter's decametric radio emission on the position of the satellite Io (Bigg, 1964).

On the other hand, as shown in Fig. 4 (due to Douglas, 1964), there seems to have been a long-term anticorrelation between Jupiter activity and sunspot number. As Douglas (1964) has pointed out, however, this result must be treated cautiously since the sunspot cycle and Jupiter's period of revolution are almost equal. Fig. 4 indicates that over the same period there is a positive correlation between Jupiter's activity and the Earth's declination as seen from Jupiter. It should also be remembered that the Sun's declination, as viewed from Jupiter, is very similar to that of the Earth, so that the data could also be taken to indicate solar stimulation of a Jovian source.

F. Correlations With Io

Perhaps the most unexpected recent discovery was that made by Bigg (1964), who showed that the probability of emission is a strong function of the position of the satellite Io relative to the Earth–Jupiter line. (Io is the innermost of the large satellites.) The occurrence probability has two maxima, one when Io's longitude is about 90° earlier than its passage across the Earth–Jupiter line, and the other 60° after it has passed this line. Bigg's results are shown in Figs. 5, 6, and 7. He has shown that the effect of Io is even more marked if only events showing emission above 30 Mc/sec are included (Fig. 7).

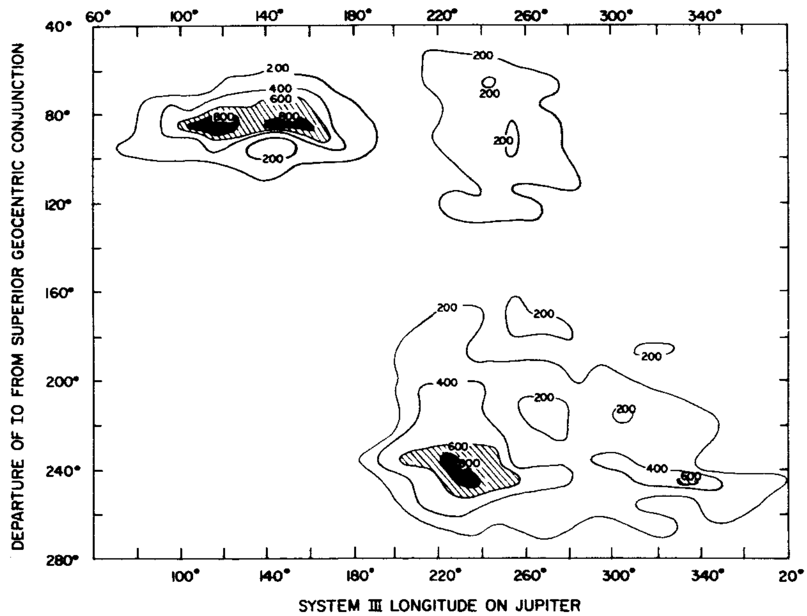

Fig. 6. The relationship between the position of Io and the orientation of Jupiter for the reception of decametric emission at the Earth (Bigg, 1964).

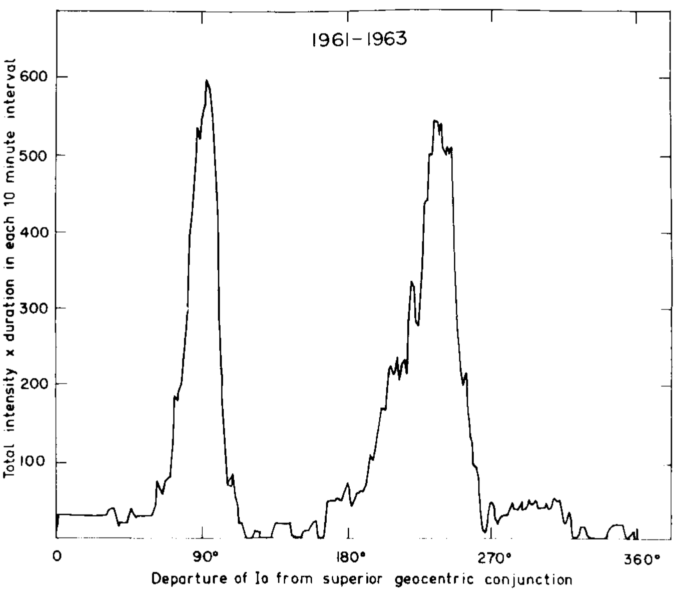

Fig. 7. Dependence of Jupiter's emission on the position of Io when only cases having top frequencies > 30 Mc/sec are considered (Bigg, 1964).

III. The Decimeter Radiation

A. Discovery

A few years after the discovery of the decametric emission by Burke and Franklin, Sloanaker (1959) of the U.S. Naval Observatory measured unexpectedly intense radiation at 10 cm. Sloanaker had previously measured an apparent disk temperature of 145 ± 20°K at 315 cm, which was in good agreement with the infrared temperature, but at 10 cm he found the disk temperature to be about 600°K, or more than four times greater.

Subsequent measurements (Drake and Hvatum, 1959; McClain, 1959; Epstein, 1959; Roberts and Stanley, 1959) confirmed this result and also indicated that the flux remains substantially constant from 10 to 70 cm, so that the effective disk temperature appeared to increase with wavelength, apparently exceeding 5 × 10^4°K at 70 cm.

It seemed unlikely that the high temperature could result from thermal processes alone, and suggestions were advanced that the radiation was produced by electrons spiralling in the assumed magnetic field of the planet. Drake and Hvatum (1959) suggested, by analogy with the terrestrial Van Allen Belt, that the radiating electrons were moving at relativistic velocities and emitting synchrotron radiation. Field (1959, 1960, 1961) also discussed this case, but considered in greater detail the possibility that the electron energies were subrelativistic and that the electrons were emitting the local cyclotron frequencies in a dipole magnetic field.

Later observations of the polarization and angular extent of the radio source have supported the synchrotron rather than the cyclotron model, but, as will be shown, the observations still show a number of features that await explanation.

B. Spectrum

The combined observations of a number of observers (Gower, 1963; Golnev et al., 1964; Haddock and Dickel, 1963; Kazes, 1964; Mayer, 1961; Roberts and Komesaroff, 1965; Roberts and Ekers, 1965; and Thornton and Welch, 1963) show that between 178 Mc/sec and nearly 3000 Mc/sec the flux density has a substantially constant value of between about 5 and 7 flux units. Beyond 3000 Mc/sec the flux density rises to some hundreds of flux units at 37,000 Mc/sec.

On the assumption that the radiation combines two components, a thermal contribution from the disk at a temperature of 130°K, and a nonthermal component with a flat spectrum from the Van Allen Belt, we should expect a rise at the higher frequencies, but in fact the observed rise is too great to be explained in this way. However, Berge (1965) has reported evidence that the disk component at 10 cm is about twice as high as would be expected from the infrared temperature of 130°K.

The flat spectrum below 3000°K also presents a problem. Assuming that the major part of the radiation comes from relativistic electrons that have an isotropic velocity distribution and gyrate in the planet's magnetic field, and making the usual assumptions of synchrotron theory, we require that the electrons have a differential energy spectrum proportional to E^{-1} (where E is the electron energy). For the Earth's Van Allen Belt, the spectrum is proportional to E^{-5}. It is not clear why there should be a relative deficiency of low-energy electrons in the Jovian Belt.

C. Polarization

1. Linear polarization. If the Jupiter radiation is produced by electrons gyrating in a magnetic field, a high degree of linear polarization might be expected, and so, following the suggestions made by Drake and Hvatum and by Field, linear polarization studies were undertaken at the California Institute of Technology. Radhakrishnan and Roberts (1960) found that the radiation was about 30% linearly polarized at 31 cm, with the maximum

E-vector in the planetary equatorial plane. Morris and Berge (1962) confirmed the 31-cm result and found a similar result at 22 cm. They also found that the more extended components of the source are more highly polarized.

Subsequent observations by Roberts and Komesaroff (1965) showed that the degree of polarization is essentially constant between 300 and 2650 Mc/sec at about 22%, or somewhat lower than reported previously. Above 3000 Mc/sec, the polarized component decreases.

The constancy of polarization with frequency up to 3000 Mc/sec certainly contradicts predictions based on a model depending on cyclotron radiation from nonrelativistic electrons. However, even using synchrotron theory, which predicts a broad spectrum of emission from the individual electrons, it is difficult to construct a plausible model that gives a spectrum of polarized emission as broad as that observed.

Another important discovery by Morris and Berge was that the direction of polarization rocks through about $\pm 10°$ as the planet rotates. This finds a ready explanation if it is assumed that Jupiter's magnetic axis, like that of the Earth, is tilted with respect to the rotational axis, since synchrotron theory predicts that the direction of polarization is determined by the directions of the magnetic field lines.

Detailed polarization studies by Roberts and Komesaroff (1965) using the Parkes pencil-beam instrument have confirmed the Morris and Berge result and have also shown that the period of the rocking agrees with the IAU System III (1957.0) period to within 0.5 sec. Roberts and Komesaroff also find that the dependence of position angle on λ_{III} shows distinct departures from the sinusoidal form that would be predicted from a simple dipole model. At both 21 and 11 cm, the second harmonic term in the "rotation curve" has an amplitude of between 5 and 10% of the fundamental. The most plausible explanation of this effect at the moment is in terms of nondipolar components in the magnetic field configuration. Explanations of the decametric burst characteristics have also required nondipolar field components.

2. ***Circular polarization.*** Roberts and Komesaroff (1965) attempted to detect circular polarization at 960 Mc/sec, using circularly polarized feeds based on a design developed by the Jet Propulsion Laboratory. The technique involved observing one sense of circular polarization, then changing the feed and observing the other sense. One set of measurements occupied 2 to 3 hours. Although the observations indicated that the long-term mean circular polarization does not exceed about 1%, they did not exclude the possibility of a component varying with the planetary rotation and having an amplitude of up to 3%.

Some recent observations by Berge and Morris (1964), appear to have demonstrated the existence of such a variable component. The aim of the measurements was to investigate the possibility of a displacement in position between the visible planet and the radio source. Their technique was to measure the interferometer visibility function, first with parallel feeds having their *E*-vectors parallel to Jupiter's rotational axis, and then with crossed feeds at 45° to the axis. The first configuration accepts almost exclusively unpolarized radiation, which includes thermal radiation from the disk. The observers were able to determine the spacing at which the fringe amplitude with this feed orientation corresponds to the first null in the visibility function of the nonthermal component alone. At this spacing the fringe amplitude corresponded to the disk component alone, which was unresolved.

In the crossed horn configuration the only contribution must come from the polarized, nonthermal radiation. Therefore, assuming all the polarization is linear, any difference in the phase of the patterns in the two configurations at the spacing described above must be due to a spatial displacement between the disk and the nonthermal source. In fact, Berge and Morris found such a phase difference; it comprised both a constant component and a component that varied quasi-sinusoidally with λ_{III}. They initially interpreted this as a displacement of the radio source from the center of the planet, the constant component representing a shift in declination and the variable component representing a shift (of about 0.4 of the planetary radius) from the axis of rotation. However, Roberts and Ekers (1965) measured the position of Jupiter relative to a nearby radio source and concluded that any displacement of the radio centroid from the axis of rotation is less than 0.15 radii.

As reported at the Arecibo conference, Berge now believes that the interferometer result may be due to a small component of circular polarization, a result that would explain the variation with λ_{III}. On this interpretation, Jupiter's magnetic moment has the opposite orientation to that of the Earth, in agreement with a result deduced by Warwick (1963) from decametric burst observations.

D. Variability

A number of authors have reported long-term variations in the Jupiter radiation, and some have suggested variations that correlate with solar activity.

From observations at 11 and 21 cm made between 1962 and 1964, Roberts and Komesaroff (1965) found no long-term variations in the total flux greater than the possible experimental error. They did find a distinct variation of about 15% with planetary rotation. However, for the same values of λ_{III}, the total flux remained constant to within 4%.

The variation with λ_{III} showed two minima per revolution, one near $\lambda_{III} = 198°$ and a shallower one near 18°. Between November 1963 and November 1964 the period of the variation agreed with the System III period to within 0.8 sec.

This variation can be explained if it is assumed that a beaming process causes the radiation to be emitted in the direction of the magnetic equator (Gary, 1963; Bash et al., 1964; Roberts and Komesaroff, 1965). In that case the tilt of the rotational axis toward the Earth, as well as the inclination of the magnetic axis with respect to the rotational axis, would account for the main features of the variation. Since the beaming of synchrotron radiation depends on the electron pitch angles, these data, together with the polarization data, provide information about the pitch angle distribution. Roberts and Komesaroff have shown that the observations are consistent with a two-component model of the electron population, one component having very flat helices (and therefore being concentrated toward the magnetic equator), and the other much more widely distributed. Measurements of the detailed brightness distribution made by Berge also seem to point to such a two-component model.

The simple analysis above does not explain all features of the observations. It is found that the observed degree of beaming with magnetic latitude depends on whether the Earth is north or south of the magnetic equator. This is additional evidence supporting the idea of nondipolar terms in the Jovian magnetic field.

IV. Conclusions

The following rather general conclusions may be drawn:

1. Both the decameter bursts and the decimeter radiation indicate the existence of a Jovian magnetic field. The decimeter radiation shows that the dipolar component of the field has its axis inclined at about 10° to the planetary rotational axis, but both types of observation indicate substantial nondipolar terms.

2. The electrons responsible for the decimeter emission appear to occur in two distinct belts, the widely distributed in latitude, and the other more closely confined to the magnetic equator.

3. The decameter observations seem to provide the best chance of estimating the magnetic field strength. The observed elliptical polarization and the constant association of spectral features with System III longitudes strongly suggest that the emission frequency is close to the local electron gyrofrequency. This would imply that field strengths in the emitting regions are as large as 10 to 20 gauss.

4. The following argument suggests that the decameter emission originates in the planetary exosphere. Both the burst occurrence probability histograms and the dependence of polarization axial ratio on System III longitude show a greater degree of symmetry at 10 Mc/sec and below than they do at 20 Mc/sec. These effects would be expected if the lower frequencies originate at greater distances from the surface of the planet, where the total magnetic field strength is lower and where the dipolar component predominates over the higher-order field terms.

   The development of large decametric arrays may provide an answer to this question by permitting measurements of the burst source position relative to the planetary disk.

REFERENCES

Barrow, C. H., 1962, *Astrophys. J.*, Vol. 135, p. 847.

Barrow, C. H., 1963, *Nature*, Vol. 197, p. 180.

Bash, F. N., Drake, F. D., Gunderman, E., and Heiles, C. E., 1964, *Astrophys. J.*, Vol. 139, p. 975.

Berge, G. L., and Morris, D., 1964, *Astrophys. J.*, Vol. 140, p. 1330.

Berge, G. L., 1964 (reported at the Symposium on Planetary Atmospheres and Surfaces, May 24–27, Dorado, Puerto Rico), *Radio Science*, Vol. 69D, p. 1552.

Bigg, C. H., 1964, *Nature*, Vol. 203, p. 1008.

Burke, B. F., and Franklin, K. L., 1955, *Nature*, Vol. 175, p. 1074.

Carr, T. D., Smith, A. G., and Bollhagen, H., 1960, *Phys. Rev. Letters*, Vol. 5, p. 418.

Carr, T. D., Smith, A. G., Bollhagen, H., Six, N. F., and Chatterton, N. E., 1961, *Astrophys. J.*, Vol. 134, p. 105.

Douglas, J. N., 1964, *IEEE Trans. Ant. and Prop.*, Vol. AP-12, p. 839.

Douglas, J. N., and Smith, H. J., 1961, *Nature*, Vol. 192, p. 741.

Dowden, R. L., 1963, *Australian J. Phys.*, Vol. 15, p. 490.

Drake, F. D., and Hvatum, S., 1959, *Astron. J.*, Vol. 64, p. 329.

Ellis, G. R. A., and McCulloch, P. M., 1963, *Australian J. Phys.*, Vol. 16, p. 380.

Ellis, G. R. A., 1965 (reported at the Symposium on Planetary Atmospheres and Surfaces, May 24–27, Dorado, Puerto Rico), *Radio Science*, Vol. 69D, p. 1513.

Epstein, E. E., 1959, *Nature*, Vol. 184, p. 52.

Field, G. B., 1959, *J. Geophys. Res.*, Vol. 64, p. 1169.

Field, G. B., 1960, *J. Geophys. Res.*, Vol. 65, p. 1661.

Field, G. B., 1961, *J. Geophys. Res.*, Vol. 66, p. 1395.

Franklin, K. L., and Burke, B. F., 1958, *J. Geophys. Res.*, Vol. 63, p. 807.

Gardner, F. F., and Shain, C. A., 1958, *Australian J. Phys.*, Vol. 11, p. 55.

Gary, B., 1963, *Astron. J.*, Vol. 68, p. 568.

Golnev, V. Y., Lipkova, N. M., and Pariiski, Yu. N., 1964, *Dok. (1964) Akad.* Nauk, SSSR, Vol. 157, p. 554.

Gower, J. F. R., 1963, *Nature*, Vol. 199, p. 1273.

Haddock, F. T., and Dickel, J. R., 1963, *Trans. Am. Geophys. Union*, Vol. 44, p. 886.

Kazes, I. N., 1964, Cornell University, Research Report, RSGI, p. 48.

Kraus, J. D., 1956, *Astron. J.*, Vol. 61, p. 182.

REFERENCES (Cont'd)

Kraus, J. D., 1958, *Proc. IRE*, Vol. 46, p. 266.

Mayer, C. H., 1961, *The Solar System, Vol. III, Planets and Satellites*, ed. by G. P. Kuiper and B. M. Middlehurst, p. 442 (Univ. of Chicago Press, Chicago).

Mayer, C. H., McCullough, T. P., and Sloanaker, R. M., 1958, *Astrophys. J.*, Vol. 127, p. 11.

McClain, E. F., 1959, *Astron. J.*, Vol. 64, p. 339.

Morris, D., and Berge, G. L., 1962, *Astrophys. J.*, Vol. 136, p. 276.

Radhakrishnan, V., and Roberts, J. A., 1960, *Phys. Rev. Letters*, Vol. 4, p. 493.

Roberts, J. A., and Stanley, G. J., 1959, *Publ. Astron. Soc. Pacific*, Vol. 71, p. 485.

Roberts, J. A., and Komesaroff, M. M., 1965, *Icarus*, Vol. 4, No. 2, p. 127.

Roberts, J. A., 1965 (reported at the Symposium on Planetary Atmospheres and Surfaces, May 24–27, Dorado, Puerto Rico), *Radio Science*, Vol. 69D, p. 1543.

Shain, C. A., 1955, *Nature*, Vol. 176, p. 836.

Shain, C. A., 1955, *Australian J. Phys.*, Vol. 9, p. 61.

Sherrill, W. M., and Castles, M. P., 1963, *Astrophys. J.*, Vol. 138, p. 587.

Slee, O. B., and Higgins, C. S., 1963, *Nature*, Vol. 197, p. 781.

Sloanaker, R. M., 1959, *Astron. J.*, Vol. 64, p. 346.

Smith, A. G., Carr, T. D., Bollhagen, H., Chatterton, N., and Six, F., 1960, *Nature*, Vol. 187, p. 568.

Smith, A. G., Lebo, G. R., Six, N. F., Carr, T. D., Bollhagen, H., May, J., and Levy, J., 1965, *Astrophys. J.*, Vol. 141, p. 457.

Smith, H. J., and Douglas, J. N., 1962, *Astron. J.*, Vol. 67, p. 120.

Thornton, D. D., and Welch, W. J., 1963, *Icarus*, Vol. 2, p. 228.

Warwick, J. W., 1961, *Annals N.Y. Acad. Sci.*, Vol. 95, p. 39.

Warwick, J. W., 1963, *Astrophys. J.*, Vol. 137, p. 41.

Warwick, J. W., 1963, *Astrophys. J.*, Vol. 137, p. 1317.