# FURTHER OBSERVATIONS OF RADIO EMISSION FROM THE PLANET JUPITER

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*Summary*

The results of further observation of Jupiter radiation, made near Sydney from June 1955 to March 1956, are presented. Most work was done at 19·6 Mc/s, but some observations were also made at 14 and 27 Mc/s.

The characteristics of the 19·6 Mc/s radiation received from Jupiter are described in detail. The new facts disclosed by these observations are: (i) Jupiter radiation appeared to be random noise varying rapidly in intensity—large changes in intensity took place in times as short as 0·2 sec, but no shorter; (ii) some spaced-receiver observations indicated that the terrestrial ionosphere can have a pronounced effect on the short-term characteristics of the radiation; (iii) a single observation showed that on that occasion the radiation was circularly polarized (right-handed in radio sense).

There appeared to be three sources of noise on Jupiter. None of these could be identified with visual features. The radiation emitted from the main source was confined to angles within 45° of a central line.

The additional observations at 14 and 27 Mc/s showed that the peak intensity, mean duration, and frequency of occurrence were all greatest at 19·6 Mc/s. Two of the radio sources were active at 19·6 Mc/s but not at 27 Mc/s. The angular spread of the radiation from the principal source was considerably narrower at 27 Mc/s than at 19·6 Mc/s.

The great variability and spectral concentration of the Jupiter radiation, both resembling solar noise, suggest an origin in some form of plasma oscillation in an ionized region with a critical frequency around 20 Mc/s.

## I. Introduction

Radio noise from Jupiter was first observed early in 1955 by Burke and Franklin (1955) at Washington, with a 22·3 Mc/s "Mills Cross" system. The intensity of the radiation was very great at 22·3 Mc/s, but appeared to fall off rapidly with increasing frequency, as no radiation was observed at all at 38 Mc/s. After the discovery was announced, a search by one of us (Shain 1955, 1956) of old records of cosmic noise taken in Sydney at 18·3 Mc/s confirmed the American observations and showed in addition that in 1951 the radiation came from a localized region on the planet. The absence of high frequency radiation was confirmed by an examination of records taken at Cambridge at 38 Mc/s (Smith 1955) and at Sydney on 85 Mc/s.

At this stage our knowledge of the basic facts concerning the radiation was too incomplete for the drawing of worth-while conclusions about the mechanism of generation of the radiation. The further observations to be described were

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an attempt to answer some of the outstanding problems. These included the spectrum and polarization of the radiation, the location and features of the planetary source, and particularly the characteristic time variations of the noise itself. The results obtained have provided only partial answers to these problems. They suggest an origin of the noise in some type of resonance oscillation in Jupiter's atmosphere, but optical data give no clues as to where or why such oscillations occur.

## II. Equipment

The observations were made at Fleurs (34 °S., 151 °E.), near Sydney, from June 1955 to March 1956. During this time Jupiter's declination varied between +15 and +20°, corresponding to zenith angles at transit of 49 and 54°. Transit was at midday on August 5, 1955 and at midnight on February 19, 1956.

Because the radiation from Jupiter is very variable and bears some resemblance to interfering signals from terrestrial atmospherics, solar noise, and radio stations, which can be very severe at frequencies near 20 Mc/s, it was

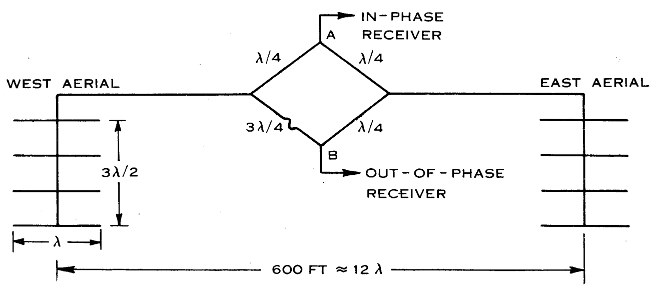



Fig. 1.—19·6 Mc/s interferometer receiving system.

considered essential to have a good system for identifying the radiation from the planet. Accordingly the main equipment comprised the 19·6 Mc/s interferometer system shown diagrammatically in Figure 1. Each aerial of the interferometer consisted of four full-wave dipoles, each a quarter-wavelength above ground, and phased to produce maximum response to the north at a zenith distance of about 50°. Since the aerial was only moderately directive in azimuth, Jupiter could be observed over a period of about 5 hr per day. The two aerials were spaced about 12 wavelengths apart in an east-west direction, so that the angle between minima of the interference pattern was about 5°. The bridge system shown in Figure 1 permitted the connexion of the aerials to two receivers which were effectively isolated from one another, one using the aerials in-phase, the other out-of-phase. Figure 2 shows a sample record obtained with this system, and also the response expected for a steady source on Jupiter. The radiation is much stronger on the " in-phase " receiver near the transit of Jupiter (at the time marked $A$ in the figure) and near $C$, 20 min earlier ; near the intermediate point $B$ it is stronger in the " out-of-phase " receiver. The system has the advantage that even short duration bursts can be identified as Jupiter radiation by the ratio of the outputs of the two receivers.

At times, observations were made with the east-west arm of the 19·7 Mc/s Cross aerial at Fleurs, a 3400 ft in-line array of dipoles one quarter-wavelength above ground, and also with a small aerial at Potts Hill, 25 km east of Fleurs.

For obtaining information on the spectrum of the radiation, single in-line arrays of four and eight half-wave dipoles were used for reception on frequencies of 14 and 27 Mc/s respectively. The dipoles were fed in-phase and their height above ground was such as to give maximum response 50° from the vertical and in the north-south plane.

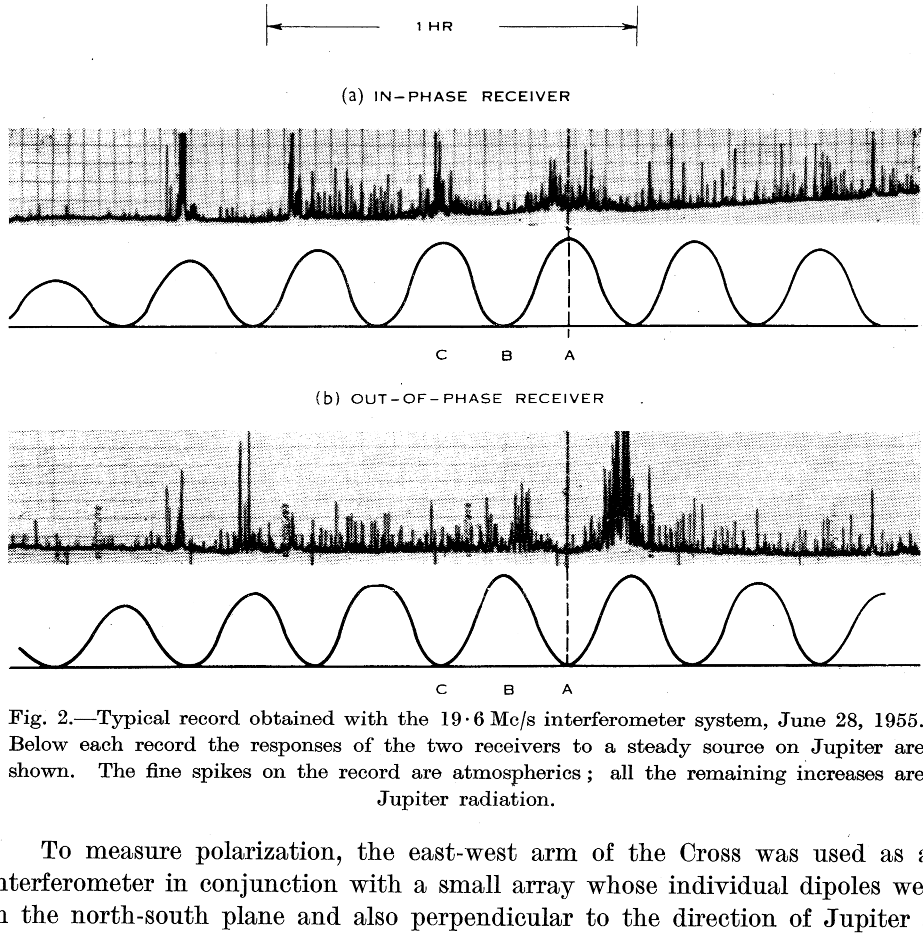



Fig. 2.—Typical record obtained with the 19·6 Mc/s interferometer system, June 28, 1955. Below each record the responses of the two receivers to a steady source on Jupiter are shown. The fine spikes on the record are atmospherics; all the remaining increases are Jupiter radiation.

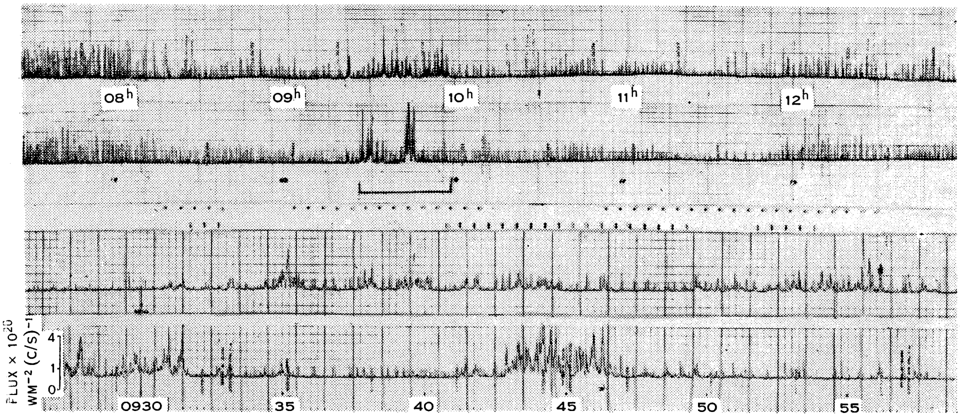
To measure polarization, the east-west arm of the Cross was used as an interferometer in conjunction with a small array whose individual dipoles were in the north-south plane and also perpendicular to the direction of Jupiter at transit. Because of the narrow beam of the long east-west array, polarization measurements were confined to times within 10 min of transit. The ratio, in amplitude and phase, of the two transverse components of the downcoming wave was measured. The method used was more accurate for phase than for amplitude.

## III. Results

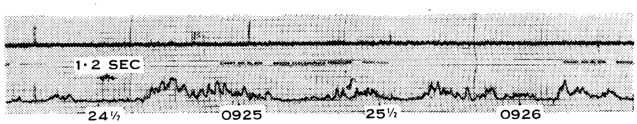
### (a) *Time Variation of the Radiation*

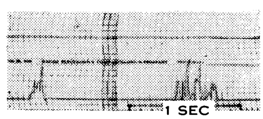
The characteristics of the radiation received from Jupiter are illustrated by the records of Figure 3 which were made at three different chart speeds. In the upper pair of records of Figure 3 (*a*), similar to those of Figure 2, the radiation from Jupiter lasts about 40 min, from about $09^h\,20^m$ to $10^h$ (sidereal time) on December 26, 1955. The radiation did not occur every day, but on days when it did occur the average overall duration of the activity was about half an hour out of the possible observing time of 5 hr.

A distinctive feature of both Figures 2 and 3 (*a*) is the occurrence of groups of bursts of radiation lasting for times of the order of a minute. They seem to be characteristic of the emission and not produced by the terrestrial ionosphere (see below). In the lower pair of records of Figure 3 (*a*), where the bracketed




(a)




(c)

Fig. 3.—Interferometer records taken with two receivers at 19·6 Mc/s. All times given are local sidereal time for Fleurs (longitude 150° 46·4′ E.). (*a*) The usual type of record ; the upper pair was taken at low paper speed, 6 in/hr, and the bracketed portion is shown below at 10 times this speed, 1 in/min, December 28, 1955. (*b*) High speed record of Jupiter taken with Brush Recorder at 20 in/min, near the time of minimum response of the in-phase receiver, November 1, 1955. (*c*) Atmospherics recorded at highest speed, 5 in/sec, one receiver only in use.

portion of the upper pair is shown with 10 times the chart speed, it can be seen that fluctuations within each burst are very pronounced. Frequent breaks of a minute or so occur, during which there is no radiation from Jupiter. The numerous short spikes on the records are atmospherics—identified as such because their envelope does not follow the characteristic interference pattern of the aerial.

To study the faster fluctuations which are not resolved in Figure 3 (*a*), a high-speed mechanical oscillograph* with a response time of a few milliseconds

* Brush Electronics Company Type BL 202, kindly lent by Mr. G. Reber.

was employed. A typical pair of records is shown in Figure 3 (*b*), from which it would appear that there are no significant bursts much shorter than 1 sec, although rise times of some bursts may be as short as one-fifth of a second; any changes faster than about $\frac{1}{5}$ sec are only of the size expected for random noise of the appropriate intensity. The shorter spikes are attributed to atmospherics, since their relative amplitudes did not follow the interference pattern of the aerial, which is near a maximum on the lower trace and a zero on the upper. The atmospherics provide a check on the response time of the system. Figure 3 (*c*) shows an atmospheric recorded at 25 times the chart speed of Figure 3 (*b*). It is seen that the receiver-recorder system can respond to sudden changes in about 10 msec, and yet on no occasion has there been any evidence for Jupiter bursts of the order of 10 msec, as reported by Kraus (1956).

When heard on a loudspeaker the Jupiter noise sounded like thermal noise varying rapidly in intensity, but only at a rate which the ear could follow. The overall impression of the noise was a resemblance to solar noise rather than terrestrial atmospherics. The time structure appeared similar to that of enhanced solar radiation at about 100 Mc/s.

An intensity scale is shown on the lowest record of Figure 3 (*a*). On this occasion the intensity was higher than usual, the peaks exceeding $4\times10^{-20}$ W m$^{-2}$ (c/s)$^{-1}$. The highest peak intensity recorded was about $10^{-19}$ W m$^{-2}$ (c/s)$^{-1}$, which is of the same order as that of a small solar outburst and more than 100 times greater than that of the strongest radio star at 20 Mc/s. On different occasions the intensity ranged from the maximum just quoted down to the minimum detectable level of about $10^{-21}$ W m$^{-2}$ (c/s)$^{-1}$.

### (*b*) *Spaced-receiver Experiment*

The angular size of the source on Jupiter is very much smaller than that of any other known radio source, and it would be expected that very severe fluctuations in intensity would sometimes be caused by scintillations in the Earth's ionosphere. In an attempt to answer the question of how important are these scintillations, a short series of simultaneous observations were made at two sites (Fleurs and Potts Hill) separated by 25 km in an east-west direction. As a precaution against spectral variations in intensity, the receivers at the two sites were tuned as closely as possible (within about 2 kc/s) to the same frequency, using a portable crystal oscillator as reference. Unfortunately there was considerable local interference at Potts Hill and the number of pairs of records available for comparison is only 3. These were taken between 23 and 02 hr local time. However, these few records are sufficient to show that there were considerable differences in the time variations of intensity at the two sites.

A striking example is shown in Figure 4, which shows the records obtained over about a quarter of an hour near $10^{h}$ sidereal time (about $23^{h}\,30^{m}$ Eastern Australian Standard Time) on February 26, 1956. The top record is from Potts Hill, and the bottom record is made up of complementary sections of the two interferometer records from Fleurs. It will be seen that, although there is a general similarity between the Fleurs and Potts Hill records, there are very marked differences. For example, the bursts recorded at Fleurs between

$10^h\,10^m$ and $10^h\,11^m$ were not recorded at all at Potts Hill, whereas the burst recorded at Potts Hill at $10^h\,03^m$ does not appear on the Fleurs records. Closer examination shows that some bursts which at first sight seem to be the same at the two sites are actually displaced in time (although not systematically) and, furthermore, the detailed structures are often quite different. Similar effects were found with the other two records, although some atmospheric and station interference prevented very detailed study.

There is the possibility that the differences between the records could be accounted for if the very slight accidental differences in receiver frequencies were accompanied by extremely sharp spectral features of the radiation. However, at various times the two receivers connected to the Fleurs interferometer have been tuned to frequencies separated by at least 10 kc/s with much smaller differences between the appearance of bursts.

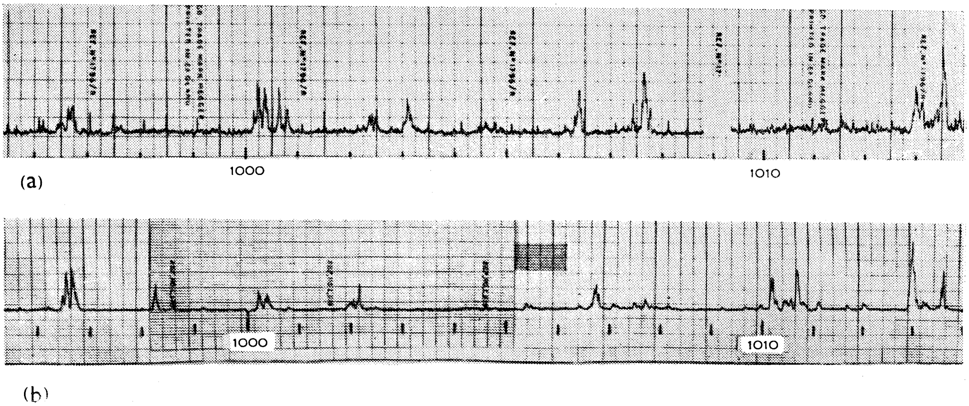



Fig. 4.—Spaced-receiver records on 19·6 Mc/s, February 26, 1956. Times are sidereal times for Fleurs. (*a*) Potts Hill—single receiver record, (*b*) Fleurs—composite interferometer record.

It must be concluded, therefore, that the terrestrial ionosphere has a considerable effect on the time variations of the Jupiter radiation. This emphasizes the necessity for caution in drawing conclusions about the true time variation from that observed. The magnitude of the effect, that is, how much of the " burstiness " of the received radiation is due to the ionosphere, can only be determined by more extensive spaced-receiver observations. However, from our knowledge of ionospheric scintillations at higher frequencies we can be reasonably sure that our general times of occurrence of Jupiter radiation are correct, and that the fine structure observed of the order of a second is a feature of the incoming radiation and not produced by the ionosphere, either by impressing fluctuations on a steady incoming signal or by lengthening by dispersion short atmospherics-like impulses.

A determination of the size and other characteristics of the irregularities which cause the terrestrial effects on the records also requires more spaced-receiver observations. The consistency of source locations from ratio measurements on individual pulses over considerable periods of time, and the definite occurrence of zeros in the interferometer records, show that the radiation reaching the ground was coherent in phase and amplitude over a distance of about 200 m. On the other hand, the present spaced-receiver experiment shows that the size of the irregularities was probably less than 25 km. It would be interesting to find out whether these irregularities are the same as those (with dimensions of about 4 km) which are studied in observations of discrete source scintillations (see, for example, Hewish 1951).

### (c) *Frequency of Occurrence of the Radiation*

The observations were practically continuous from mid July 1955 until the end of March 1956. The histogram of Figure 5 (*a*) gives the number of days in each month on which Jupiter radiation was definitely received with the interferometer. There was a maximum of recorded activity in November when radiation was identified on about one day in three.

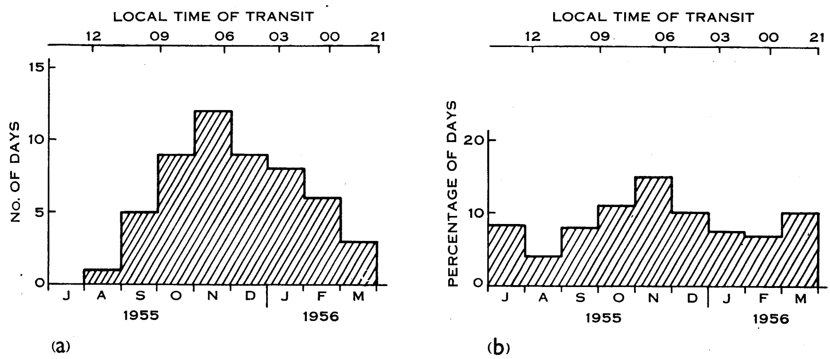



Fig. 5.—Monthly frequency of detection of Jupiter radiation on 19·6 Mc/s, (*a*) with the interferometer receiving system, and (*b*) with the receiving system using the east-west array of the Cross aerial.

The apparent variation in Jupiter activity shown in Figure 5 (*a*) is likely to be affected by the masking effect of interference, the average level of which varies greatly with time of day. If this is so, the observed frequency of occurrence would be expected to depend on the local time of transit, with a maximum during the early morning hours when interference is generally low. Figure 5 (*a*) does suggest such an effect. Observations with the east-west array of the Cross are less susceptible to interference, and the variation in the apparent frequency of occurrence of Jupiter radiation observed with this equipment, shown in Figure 5 (*b*), is considerably less than in Figure 5 (*a*). There may, however, be a true maximum in Jupiter activity in November.

### (d) *Spectral Observations*

Besides the observations on 19·6 Mc/s, additional observations were made, between November and March, on frequencies of 27 and 14 Mc/s. On any day only one of the additional frequencies was used, together with the comparison frequency of 19·6 Mc/s. The information obtained on 27 Mc/s is more complete and will be considered first.

Between November 1955 and February 1956, when Jupiter was transiting between midnight and sunrise, interference on 27 Mc/s was negligible (ionospheric critical frequencies were low and long-distance propagation consequently poor) and there was no trouble from false identifications. The 27 Mc/s equipment was operating on 52 days, and the number of occasions on which Jupiter radiation was observed on these days is set out in Table 1.

Table 1

COMPARISON OF SIMULTANEOUS OBSERVATIONS ON 19·6 AND 27 Mc/s

| Frequency on which Jupiter Radiation was Observed | Number of Days |
|---|---|
| 19·6 Mc/s but not 27 Mc/s | 10 |
| 27 Mc/s together with 19·6 Mc/s | 10 |
| 27 Mc/s but not 19·6 Mc/s | 0 |
| No radiation at either frequency | 32 |
| Total number of days on which the 27 Mc/s equipment was operating | 52 |

The remarkable feature of Table 1 is that on no occasion was radiation observed on 27 Mc/s but not on 19·6 Mc/s, even although all increases in noise on 27 Mc/s when Jupiter was in the aerial beam, other than atmospherics, were classed as Jovian.

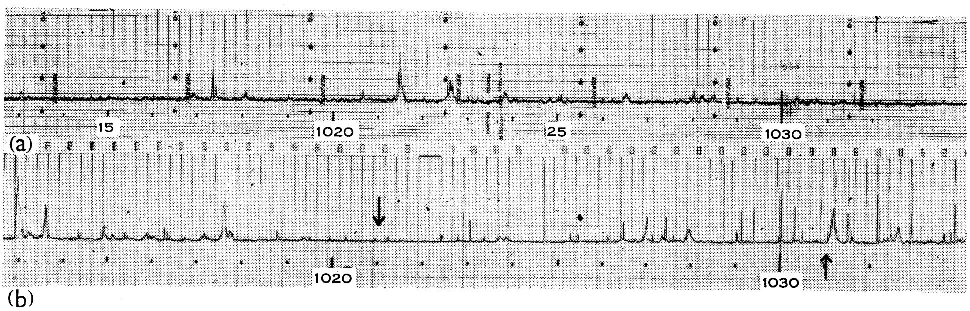



Fig. 6.—Jupiter radiation on two frequencies at Fleurs, February 26, 1956, (*a*) 27 Mc/s—single aerial record, (*b*) 19·6 Mc/s—interferometer record, the time of maximum response is shown by an upward-pointing arrow and the time of minimum response by a downward-pointing arrow.

Figure 6 shows simultaneous records at the two frequencies. A few bursts seem to occur on both frequencies, but the majority do not. The agreement in Figure 6 is probably worse than usual, but during any period of activity common to both frequencies, no more than half the bursts appeared on the two frequencies. We do not know to what extent these differences are due to the ionosphere. From our limited spaced-receiver observations it would appear the bursts on two frequencies at one site differ more than bursts on the one frequency but at spaced sites. The peak intensity on 27 Mc/s was generally only about one-third of that on 19·6 Mc/s, and on those days on which 27 Mc/s radiation was received the duration of the activity was only about one-half of that on 19·6 Mc/s. It is quite clear that there was a large decrease in the overall activity with an increase of operating frequency of only 7·4 Mc/s (that is, about one-third of 19·6 Mc/s).

The results obtained at 14 Mc/s were seriously limited by frequent severe station interference near this frequency. However, unless the association between days of activity on 14 and 19·6 Mc/s is worse than between 19·6 and 27 Mc/s, it is reasonably certain that both the peak intensity and the mean duration of active periods on 14 Mc/s are lower than on 19·6 Mc/s. This is not thought to be due only to the greater ionospheric attenuation on this frequency. When the 14 Mc/s observations were made, at night-time between November 1955 and January 1956, the *F*-region critical frequency was usually below 5 Mc/s near the time of transit of Jupiter, and with an angle of incidence on the ionosphere of about 45° the attenuation of 14 Mc/s radiation should be small. This conclusion is supported by observations of solar bursts made with about the same angle of incidence but during the day-time when critical frequencies were higher. Peak intensities of the *solar bursts* on 14 Mc/s were approximately twice those on 19·6 Mc/s.

Table 2

SPECTRAL OBSERVATIONS OF JUPITER RADIATION

| Frequency | Results | |
|---|---|---|
| 27 Mc/s | Peak intensity .. .. .. | $\approx\frac{1}{3}$ of 19·6 Mc/s |
| | Mean duration of active periods | $<\frac{1}{2}$ of 19·6 Mc/s |
| | Frequency of occurrence (day by day) .. .. .. | $\approx\frac{1}{2}$ of 19·6 Mc/s |
| 14 Mc/s | Peak intensity .. .. .. | <19·6 Mc/s |
| | Mean duration of active periods | <19·6 Mc/s |

The spectral information is summarized in Table 2. The table indicates a maximum in the level of activity between 14 and 27 Mc/s; the maximum is probably below 20 Mc/s.

We have no evidence for progressive changes in the frequency structure of the radiation, e.g. frequency drifts, of the type often found in solar noise.

### (*e*) *Polarization*

The only good record with the polarization apparatus was obtained on January 24, 1956. The longitude of the central meridian was then near 300° in System II and the most active source was being observed (see below). The downcoming wave was then approximately circularly polarized with a right-handed sense of rotation (adopting the radio-astronomical convention of looking along the direction of travel, in this case from Jupiter to the Earth). The two transverse components, in and at right-angles to the plane of incidence, were equal, within a factor of 3 to 1 in amplitude, while their phase difference was $90\pm25°$.

This result agrees with that of Franklin and Burke (1956) from observations at Washington. If the sense of rotation is indeed the same when observed in both the northern and southern hemispheres (and obviously more observations are required), the terrestrial ionosphere cannot be the medium which impresses circular polarization on the Jupiter radiation.

### (*f*) *Variation of Activity with the Rotation of Jupiter*

In the previous paper (Shain 1956) it was shown that Jupiter radiation in 1951 had a strong tendency to recur at intervals of a rotation period, an indication that the active centres on the planet were of small area and persisted for more than one rotation. This recurrence tendency was still prominent in 1955–56. The earlier part of the combined Sydney and Washington data has been discussed by Alexander (1956). Here we consider only our own observations and all the results are included. Washington results give a similar picture (Franklin and Burke 1956).

The recurrence tendency is shown by the arrangement of the observational data in Figure 7. The times of reception of Jupiter radiation have been converted to central meridian longitudes in System II. In this system 360° corresponds to the rotation period of $9^h\ 55^m\ 40^s$.

The tendency for the lines to fall under one another is very marked, and it can be concluded that the principal source of the radio disturbance near longitude 320° was revolving with a speed close to that of System II, and persisted for the full 7 months, or some 500 revolutions.

To estimate the rotation period more closely, the central time of the activity on each day was noted and the dashed line in Figure 7 shows the least squares line of best fit to all the data. It corresponds to a rotation period of $9^h\ 55^m\ 34^s$ ($6^s$ faster than System II), with a standard deviation of $9^s$. However, it will be shown in Figure 8 (Section III (*g*) below) that the data can be divided into three groups, and, if the analysis is restricted to the main source, which is observed over only 60° of longitude, the rotation period is found to be $9^h\ 55^m\ 30^s$ with a standard deviation of only $3^s$. The source was therefore moving significantly faster than System II. The speed of rotation was apparently slower than that of the source observed in 1951 (rotation period $9^h\ 55^m\ 13^s$, Shain 1956) but as the standard deviation for a similar analysis of the 1951 data is $30^s$ (a rough estimate of the probable error was previously given as $\pm 5^s$) the difference may not be significant.

There are suggestions of two disturbances following System I (rotation period $9^h\ 50^m\ 30^s$) from September to November, each producing an increase in overall activity as it crosses the line of the principal source, but the data are too few to be conclusive.

The 1951 results indicated a possible connexion between the source of the radio disturbance and a white spot (referred to as DE) at the southern edge of the South Temperate Belt (S.T.B.). Thin lines in Figure 7 show the positions, during the current period, of this and two other similar spots, in the S.T.B., taken from optical observations quoted by Alexander (1956). The arrow at the bottom of the figure shows the position of the centre of the Red Spot, whose longitude was constant over the period. There is no obvious connexion between possible sources of the radiation and any of the S.T.B. spots, and certainly they cannot be the principal source. The proximity of the Red Spot to the principal source suggests a coincidence, but there are systematic differences in longitude

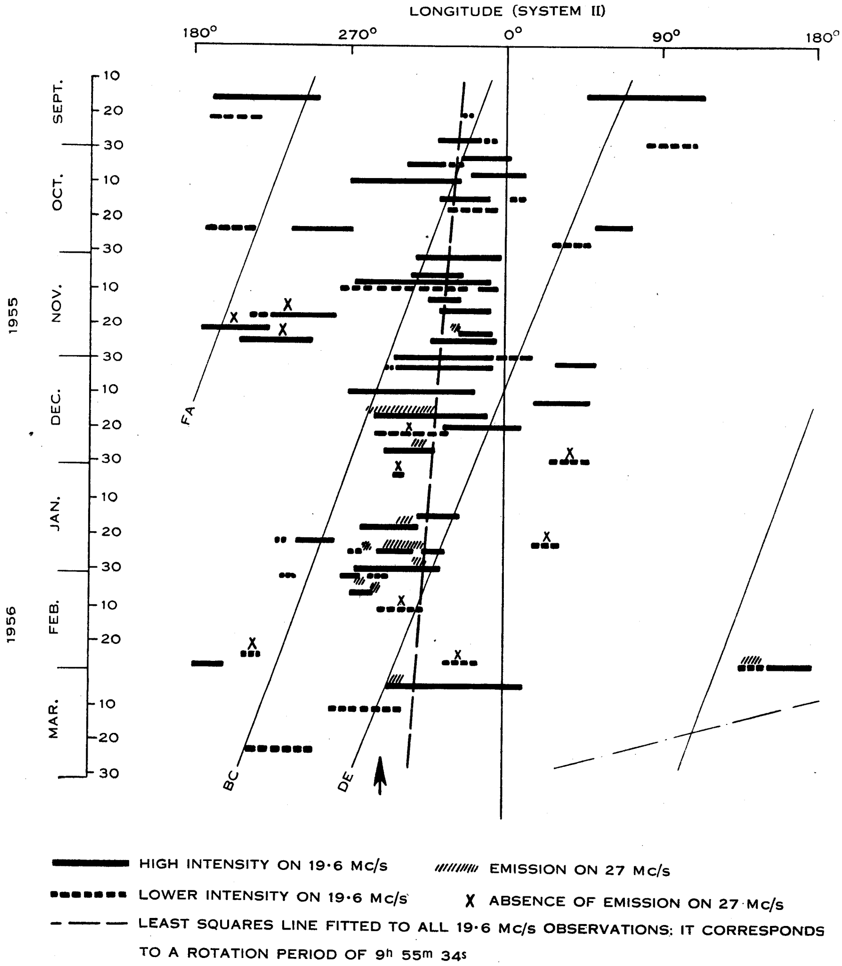



Fig. 7.—Diagram showing central meridian longitude (System II) of Jupiter at times of observed radio emission. The positions of three white spots, FA, BC, and DE, are shown by thin lines—and the Red Spot by an arrow ↑. The slope on this diagram of a source moving with System I speed is shown —·—·—.

and, more important, in rotation periods and it is most probable that the near coincidence is fortuitous. It is worth noting that the Red Spot was definitely not the main source of the 1950–51 radio noise.

In an attempt to obtain some positive identification of the radio source, plans were made for simultaneous visual observations of Jupiter at times of radio activity, but exceptionally bad weather prevented any useful work along these lines.

*(g) Angular Spread of the Emitted Radiation*

Following the procedure used previously with the 1951 observations, all the lines for the 19·6 Mc/s observations in Figure 7 were superimposed, with allowance for the slight drift in longitude, to give the histogram of Figure 8.

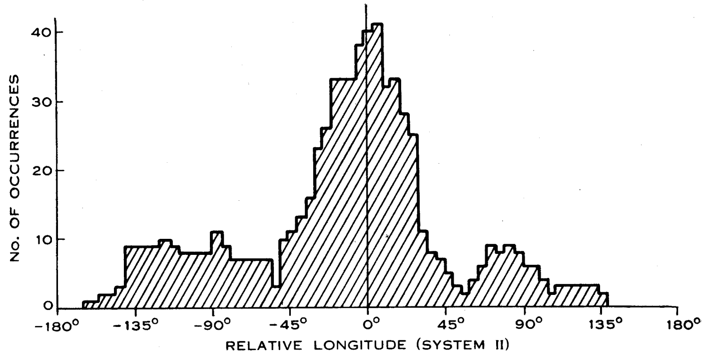



Fig. 8.—Variation of frequency of occurrence of 19·6 Mc/s radiation from Jupiter with central meridian longitude (System II) measured relative to the least squares line of Figure 7.

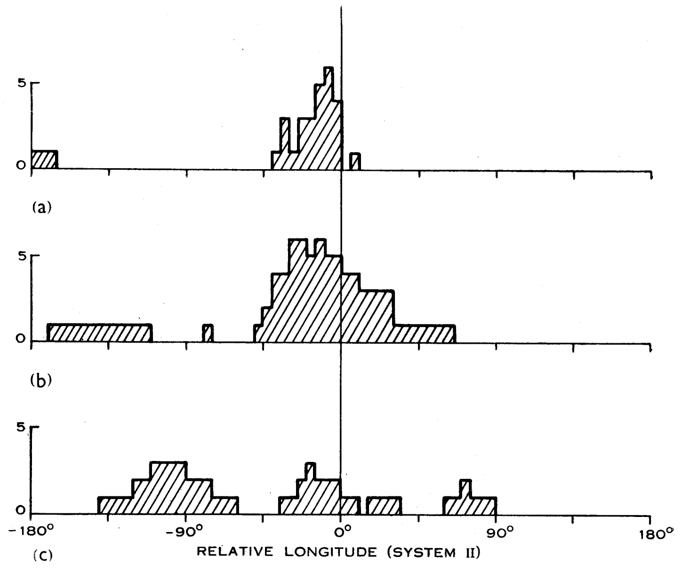



Fig. 9.—Variation of the frequency of occurrence of Jupiter radiation with central meridian longitude measured relative to the least squares line of Figure 7, (*a*) 27 Mc/s, (*b*) 19·6 Mc/s on same days as 27 Mc/s radiation was observed, (*c*) 19·6 Mc/s on days when there was no observable radiation on 27 Mc/s.

This figure shows the frequency of occurrence of Jupiter radiation for 5° intervals of longitude, measured relative to the dashed line in Figure 7. The emission from what we have taken to be the principal source can be seen to fall almost to zero at longitudes 45° from the maximum. The other two peaks, at relative longitudes $-100°$ and $+80°$, are probably due to independent sources. Figure 8 gives something rather equivalent to the average " polar diagram " of the emission from these sources. On the reasonable assumption that the vertical scale is equivalent to a scale of power, the " beamwidth " of the sources of radiation would be about $\pm 30°$ to half-power.

Histograms were compiled in a similar way to compare the 19·6 and 27 Mc/s results. Figures 9 (*a*) and 9 (*b*) show histograms for 27 and 19·6 Mc/s on days on which 27 Mc/s radiation was received, and Figure 9 (*c*) for 19·6 Mc/s for days when there was no observable radiation on 27 Mc/s. The longitude scale is the same as that in Figure 8. The absence in Figures 9 (*a*) and 9 (*b*) of the prominent peaks at $-100°$ and $+80°$ is the result, previously noted above, that some sources radiate on 19·6 but not on 27 Mc/s. This supports the conclusion that the three peaks in Figure 8 are associated with independent sources of radiation.

When attention is restricted to the principal source, common to both frequencies, we see clearly from Figure 9 that the angular spread of its radiation is much narrower on 27 Mc/s than on 19·6 Mc/s. The result is also found that 27 Mc/s activity occurred, on the average, only during the early part of 19·6 Mc/s activity. That is, the histogram in Figure 9 (*a*) is significantly displaced with respect to the histogram of the principal source in Figure 9 (*b*).

## IV. Discussion

The main facts uncovered in the present investigation may be summarized as follows :

(i) The radiation lasted for periods of about half an hour and was made up of short bursts lasting for times of the order of 1 sec. Over several months Jupiter was active for only about 5 per cent. of the time.

(ii) The intensities of the bursts were very high, attaining a peak of about $10^{-19}$ W m$^{-2}$ (c/s)$^{-1}$.

(iii) Marked differences were observed between records of radiation made simultaneously at stations 25 km apart.

(iv) The intensity and frequency of occurrence was about 2 or 3 times greater on 19·6 Mc/s than on 14 or 27 Mc/s.

(v) From one record only in Sydney (with confirmation from Washington) the radiation was approximately circularly polarized.

(vi) During the period of the observations there were three sources of 19·6 Mc/s radiation ; none of these can be identified with visual features. Only one of these sources, the most active, radiated appreciably on 27 Mc/s as well as on 19·6 Mc/s. Its rotation period was $9^{h}\,55^{m}\,30^{s}$, locating it outside the equatorial regions of the planet.

(vii) The angular spread of the radiation was 60° at 19·6 Mc/s but only about 30° at 27 Mc/s. The longitudes of the central meridian for the 27 Mc/s activity were asymmetrically disposed with respect to those for 19·6 Mc/s.

Although it is clear from the spaced-receiver experiment that the terrestrial ionosphere has a pronounced effect on the short-term characteristics of the received radiation, we consider that the items listed above (with the exception of (iii)) describe the general variation of the activity of the sources on Jupiter. In the light of these data we may consider possible mechanisms of the origin of the radiation.

The rapid variations in intensity and the extremely high brightness temperatures required—above $10^{13}$ °K, even on the unlikely assumption that the whole disk emits uniformly—make thermal radiation most unlikely. The observed Jupiter radiation differs from terrestrial atmospherics and cosmic noise particularly in its very restricted spectrum. There has been no sign of Jupiter radiation at 38 Mc/s (Burke and Franklin 1955; Smith 1955), a frequency only twice that at which the intensity is a maximum. Such a high frequency cut-off is much more rapid than that found with either of these sources of noise.

Radiation from the Sun, however, sometimes resembles Jupiter radiation in its great variability and spectral concentration, and similar origins are possible. This would require on Jupiter an ionized region with a plasma frequency, or possibly a gyrofrequency, of about 20 Mc/s. The polarization results imply a magnetic field. The ionized region could be excited into oscillation by some form of electrical discharge, or the passage of a shock wave (perhaps originating in some volcanic disturbance).

The restricted spectrum and the constancy of the frequency of maximum intensity over long periods of time suggest a complete layer of ionization surrounding Jupiter, similar to the terrestrial ionosphere. Solar radiation is the most likely source of such ionization, although, at first glance, it would be expected that critical frequencies would be considerably lower than on the Earth. If plasma oscillations are responsible for the radiation, the decay times should approximate $\nu^{-1}$, where $\nu$ is the collision frequency (Jaeger and Westfold 1949). The observed decay times of about 0·5 sec suggest that the ionized layer is relatively higher on Jupiter than on the Earth ($\nu^{-1}=10^{-3}$ in the $F$ region).

It is difficult to explain the restricted angular spread of the emitted radiation and its further decrease with increasing frequency. While effects from refraction and absorption by ionized material above the level of emission could produce a narrower beam, they would simultaneously cause an opposite frequency variation, a beam widening towards higher frequencies. This effect might be offset if the higher frequencies originated at greater depths in Jupiter's atmosphere. It should also be noted that, if the angular spread of the radio emission is the same in latitude as in longitude, it is possible that the two sources which did not appear to have radiated on 27 Mc/s are in higher latitudes than the principal source, the narrower "beamwidth" on 27 Mc/s cutting off emission in the direction of the Earth.

Related to the question of the narrower beamwidth at 27 Mc/s is the asymmetry of the 27 Mc/s radiation pattern with respect to 19·6 Mc/s. One important possibility which must be considered is that the 27 Mc/s observations give the true longitude of the source, and the broader, asymmetrical beam at 19·6 Mc/s is due to differing propagation conditions before and after noon on Jupiter. This would affect any optical identifications, but the matter can only be resolved by extensive observations at more than two frequencies.

## V. Conclusion

The great gap in our present knowledge of Jupiter radio emission is still the lack of any definite identification of the source of the noise with visual features, so that there is no direct tie-up between radio and visual observations. Simultaneous visual and radio observations are the outstanding requirement. It is short-term (order of half an hour) changes in the visual appearance which must be looked for. It must be remembered that the radio source may be situated high in Jupiter's atmosphere so that direct visual observation of the source may prove impossible.

As regards radio observations, the important points requiring elucidation are the magnitude of the effect of the terrestrial ionosphere and the nature of the dynamic spectra of the bursts. On a longer-term basis, observations over an appreciable fraction of a sunspot cycle may help to determine the importance of solar photo-ionization in Jupiter's atmosphere, but such observations must be calibrated for intensity more accurately than has been done in the past.

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