Decametric Radiation from Jupiter

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Summary—**A brief historical summary is followed by a review of current observations of Jupiter's decametric radiation. Particular attention is given to the time structure and statistical properties of the emission, and several important deficiencies in our observational knowledge are pointed out.**

I. Introduction

THE SERENDIPITOUS discovery of decametric radiation from Jupiter was made by Burke and Franklin [1], [26] while using the Mills Cross of the Carnegie Institution of Washington for a survey of the sky at 22.2 Mc. During the first quarter of 1955, a strong, fluctuating noise appeared on 10 out of 31 nighttime records of a declination strip centered at $+22°$. Nine of these noise events, although resembling terrestrial interference, occurred at approximately the same sidereal time and never lasted longer than the time it would require for a sidereal source to pass through the antenna's $1\overset{\circ}{.}6\times2\overset{\circ}{.}4$ beam. The events could be explained by an intermittently-active fluctuating extraterrestrial noise source having a right ascension approximately equal to the median time of occurrence of the noise. The right ascension thus observed coincided with that of Jupiter, then at a declination near $+22°$. Furthermore, the apparent right ascension of the noise source was observed to change over a three month period, precisely reflecting Jupiter's geocentric motion. This irrefutable association of an intense and obviously nonthermal decametric noise source with Jupiter marked the beginning of planetary radio astronomy.

Nearly ten years of observation have established the decametric radiation as a phenomenon of great complexity; decisive proof of any theory is lacking. This review will concentrate on observations, sketching the current (incomplete) picture of the decametric radiation.

II. Results of Early Work

A. Discovery Observations

Three fundamental characteristics of the radiation were established in Burke and Franklin's original observations:

1) Records obtained on 22 of 31 nights showed no evidence whatever of radiation from Jupiter; thus, the radiation is seen to be *sporadic*, occurring in noise storms with durations of less than a day.
2) A noise storm was composed of a sequence of bursts, many of which were shorter than the 15-sec recorder time constant; tape recordings showed them to be 0.1 to 1.0 sec long, superimposed on a rather smooth rise and fall of background noise. Thus, the radiation when present is *fluctuating*.
3) In only two cases was the flux less than that of the Crab Nebula, the other seven being much stronger, occasionally driving the recorder off scale. The flux from the Crab Nebula, measured with the Mills Cross, was 5×10^{-23} wm^{-2} cps^{-1}. This was 10^8 times the expected thermal flux from Jupiter at this wavelength. Consequently, the radiation is extraordinarily *intense*.

B. Prediscovery Observations

The intensity of the decameter source makes it noticeable even on records taken for quite different purposes, where it might well have been mistaken for terrestrial interference. Accordingly, available records were checked, and a number of workers announced prediscovery observations, suggesting further important characteristics of the radiation.

1) *Spectral Limitation:* Observations of the occultation of the Crab Nebula (then near Jupiter) by the sun were made in 1954 at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, with simultaneous records obtained at 22.2, 38, and 207 Mcs. Burke and Franklin [4], [25] report eight periods of apparent Jupiter activity on 22.2 Mc; in no case was this accompanied by activity on either higher frequency, although the sensitivity of the higher frequency equipment was greater. This result was indirectly confirmed by F. G. Smith [5], who searched 38 and 81.5 Mc records obtained with very high sensitivity radio interferometers at the Cavendish Laboratories, Cambridge, England, finding no instance of Jupiter activity on either frequency.

2) *Typical Duration:* The discovery observations were made with a pencil beam instrument which was sensitive to Jupiter only fifteen minutes a day; consequently, it could be said only that the duration was less than a day. Shain [3], [6] obtained extensive prediscovery observations in the course of an 18.3 Mc cosmic noise survey in 1950 and 1951. Shain's apparatus was sensitive to Jupiter for two to eight hours per day; in spite of this, noise storms were typically less than two hours long. Thus, the apparent flux from the source may change over two orders of magnitude in times of the order of one hour.

3) *Correlation with Rotation:* Optical observers can measure the rotation period of various long-lived features in the upper cloud layers (*e.g.*, the white spots or

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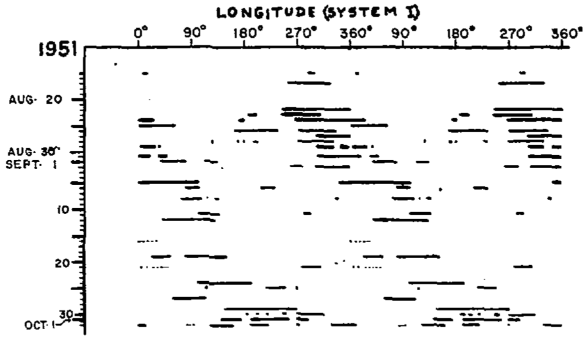
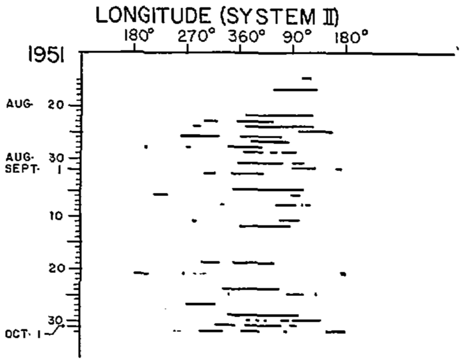


(a)



(b)

Fig. 1—Central meridian longitude during decametric noise storms as a function of observational data: a) using System I longitudes, b) using System II longitudes. (From Shain, [6].)

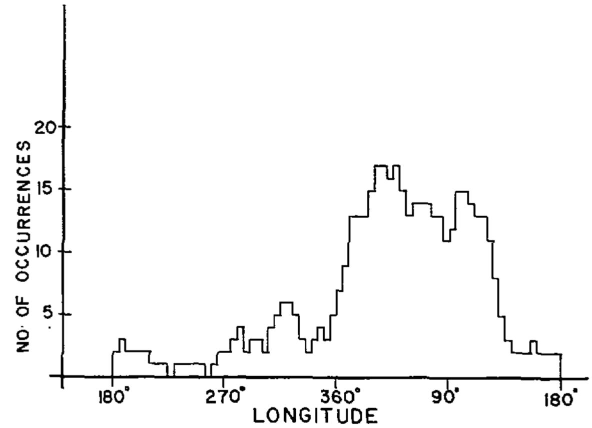


Fig. 2—Number of occurrences of 18.3 Mc radiation per 5° interval of central meridian longitude. Longitude system agrees with System II on August 14, 1951, and rotates with a period of $9^h\ 55^m\ 13^s$ (From Shain, [6].)

the Great Red Spot) by timing the interval between successive passages of the object across the central meridian of the planet's disk. No two periods obtained in this way are exactly the same; apparently the features are floating in the upper atmosphere. However, features in the equatorial regions tend to rotate with a period near 9^h50^m, and those in temperate and polar regions, with a period near 9^h55^m. Two longitude systems have been defined, suitable for equatorial and temperate regions respectively. System I (rotating in $9^h50^m30.^s003$), and System II (rotating in $9^h55^m40^s.632$). To check for possible correlation, Shain [3], [6] plotted periods of occurrence of radiation against longitude of the central meridian at the time of observation, for both System I and System II. Fig. 1 reproduces his original diagram. It is clearly not a random distribution, the most frequently occurring longitude drifting with date in System I. This drift is slightly overcorrected in the System II plot, suggesting the best fit would be with a period slightly shorter than that of System II. The deviation is not remarkable, but the distinct correlation with rotation certainly is.

4) *Directivity of Radiation:* Re-expressing Fig. 1(b) in terms of a period of $9^h55^m13^s$, Shain summed the number of occurrences per 5° region of central meridian longitude, obtaining the *occurrence frequency* histogram reproduced here as Fig. 2. The region of most frequent occurrence is only 135° wide, not 180° as would be expected for an isotropic source localized on the planet.

5) *Other Prediscovery Observations:* On several occasions in 1953 and 1954, Reber [31] observed radiation near 30 Mc which later seemed best interpreted as that of Jupiter. No other prediscovery observations have been reported; Jansky's original 13-m cosmic noise records very probably contained many instances of Jupiter radiation, but they are unfortunately lost or destroyed. As a result of inquiries by Smith [85], and with the cooperation of V. Agy, at National Bureau of Standards, Boulder, Colo., 20 years of 24-hour field-strength records obtained by A. M. Braaten of RCA's receiving station at Riverhead, L. I., N. Y., have been scanned. Although obtained with sensitive equipment and beautifully annotated by Braaten, the records were unfortunately obtained with a logarithmic, discrete-step recorder, and Jupiter radiation is not in evidence.

C. First Observation Programs

Following the discovery of decametric radiation, Jupiter observation programs were established at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington (Burke and Franklin [11], [18] and Franklin and Burke [7], [25]), Commonwealth Scientific and Industrial Research Organization (Gardner and Shain [20]), National Bureau of Standards (Gallet [13], [44]) and Ohio State University (Kraus [8], [19], [29]). Observations obtained by these groups during the 1956 and 1957 oppositions completed the initial description of the radiation characteristics.

1) *Multifrequency Observations of Longitude Profile:* [7], [9], [11], [13], [20], [25]. Occurrence frequency histograms, similar to Fig. 2, were obtained at 27, 22.2, 19.6, 18, and 14 Mc for the 1955–56 opposition. Their general appearance near 20 Mc was consistently trilobed, with one region much more active than the other two; in addition, a prominent quiet region occupied 40–60° of longitude. The principle region seemed narrower than in Shain's 1951 observation—about 50° wide. An increase in occurrence probability, flux, and width of

major peak with decreasing frequency was noted by all observers; Gardner and Shain [20] noted a shift in the longitude of the major peak to earlier longitudes at 27 Mc. The tri-lobed profile was generally interpreted as signifying the existence of three or more sources on the planet.

2) *Narrow Bandwidth of Radiation:* [7], [9], [11], [13], [20], [25]. Initial indications of sharp spectral characteristics were abundantly confirmed when it was found that activity on any frequency was not necessarily accompanied by activity on frequencies 2 Mc higher or lower. Good correlation over 0.1 Mc was observed, establishing the radiation as relatively narrow band, with a bandwidth somewhere between 0.1 and 2 Mc. Center frequencies between 14 and 27 Mc were apparently possible, and on one occasion, Kraus [19] reported radiation as high as 43 Mc.

3) *Time Structure:* High-speed recordings by Kraus [8], [19] and by Gallet [13], [44] and Gallet and Bowles [9] produced evidence of amplitude variation in times on the order of milliseconds, as well as the slower 0.1 to 10-sec fluctuations noted earlier. Gardner and Shain [20] noted only the slower component, and found that the time structure was markedly different when observed with receivers 25 km apart, suggesting the presence of important ionospheric effects.

4) *Solar Correlation:* An inverse correlation of occurrence probability with sun-spot number for 1956 and 1957 was found and interpreted by Gallet [9], [13] in terms of effects imposed by a Jovian ionosphere.

5) *Rotation Period:* Both Gallet [13] and Burke [18] commented on the persistence of the relative position of peaks on the longitude profile with time as evidence that the sources are fixed, perhaps on the solid body of the planet. Based on a comparison of current data with the prediscovery data of Shain [3], [6], Gallet calculated a radio source rotation period of $9^h55^m29.^s5$, and Burke a period of $9^h55^m28.^s5$.

6) *Polarization:* Observations with a crossed-dipole interferometer at the Department of Terrestrial Magnetism of the Carnegie Institution [11], [25] showed the radiation to be predominantly right-hand circular; simultaneous observation of one event by Gardner and Shain [20] showed a similar sense of polarization in the southern hemisphere, thereby ruling out a terrestrial ionospheric effect. This strongly implied the presence of a magnetic field on Jupiter. Based on a source beneath Jupiter's ionosphere with one magnetoionic mode cut off by the ionosphere, Burke and Franklin [11] gave a lower limit to the magnetic field of 4 Gauss.

At the conclusion of these initial observations, the decametric radiation was regarded as 1) sporadic, b) directional and rotating with Jupiter, c) narrow band, d) polarized, and e) affected both by average solar activity and by the terrestrial ionosphere. Observations were widely interpreted in terms of several sporadically emitting sources on the "solid" surface of Jupiter, whose radiation was affected by the Jovian ionosphere.

III. Apparent Time Structure

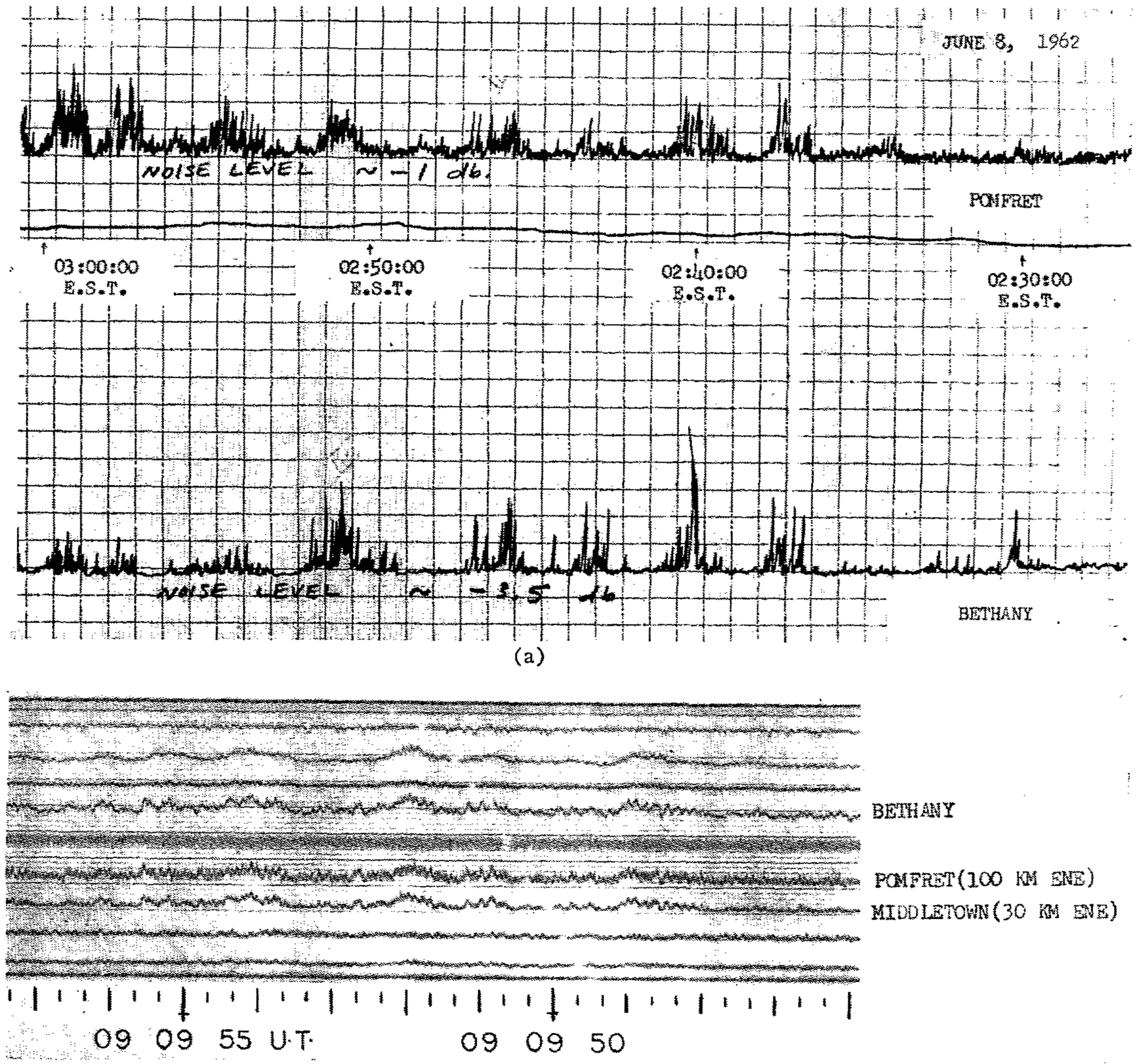
No feature of the decametric radiation is better established than its intermittent behavior; however, one must be careful to distinguish the *apparent* time structure of the radiation from the *intrinsic* behavior of the source of the radiation. Apparent time variability may arise partly or entirely from a changing center frequency and orientation of a narrow-band, directive emission source, together with ionospheric scintillation effects. The relaxation time of the emission mechanism, important for theoretical discussion, can only be obtained by a simultaneous study of the apparent time structure, spectum and directivity of the source, after elimination of possible time-varying propagation effects.

The decametric radiation is known to be variable on several times scales: short (rapid flux variation during a noise storm), moderate (noise storm duration, rotation correlation), and long (correlation with sun-spot cycle). This section will summarize present knowledge of time behavior on the shortest scale, the substructure of noise storms.

A. *Time Structure of Noise Storms*

Early single-frequency observations established the apparently hierarchical substructure of noise storms. Flux variations, although random in nature, appeared to be composed of variations on three well-separated time scales: minutes, seconds, and, on rare occasions, tens of milliseconds. The 22.2 Mc Jupiter storm in Fig. 3(a) is seen to be composed of clumps of radiation, or burst groups, each lasting a minute or two and possessing unresolved fine structure. Fig. 3(b), made with a high-speed photographic recorder and time constant of 30 msec, shows 10 sec of a burst group. The spike-like structure unresolved in 3(a) is seen in 3(b) as a gentle rise and fall of a second's duration; following Gallet [44], we will call these L pulses. Superimposed on the L pulses, shorter pulses are seen; these are presumably the "clicks" first reported by Kraus [8], [19] in 1956, and the S pulses discussed by Gallet [45]. Some S pulses have rise times limited by the time constant of the recording pen, or less than 30 msec. Systematic studies of the durations of the S pulses and burst groups are lacking; however, Douglas [38] has reported a statistical study of duration of L pulses indicating that on one night, 99 per cent had durations between $0.^s3$ and $2.^s0$ with a most frequent duration of $0.^s6$. Since all S pulses have durations$\ll 0.^s3$, and all burst groups have durations$\gg 2.^s0$, three separate processes may well be responsible for this.

Not all noise storms possess all three elements of time structure discussed above. The S pulses are relatively rare; when present, they usually continue throughout the entire storm. Burst groups may merge, giving the storm the appearance of 10 or 15 minutes of rather continuous burst-like activity. L pulses are almost continuous emissions with bursts superimposed. Weak continuous emission is frequently seen as a precursor to a



(b)

Fig. 3—(a) Jupiter 22.2 Mc total-power tracings produced on a common recorder by a set of identical antennas and receivers located at Bethany and Pomfret, Connecticut, separated by 100 km on an ENE line. (b) A 10-sec portion of a high-speed recording of the Jupiter storm of July 18, 1961, showing close correlation of fine structure at three spaced receivers.

period of violent burst activity and remains after burst activity has ceased (Fig. 4, 02:24:00 to 02:50:00 E.S.T.).

B. Spaced Receiver Observations

Diffraction effects in the terrestrial ionosphere are known to produce violent amplitude fluctuations on radiation received from discrete radio sources on a time scale of minutes to tens of seconds. Such fluctuations are uncorrelated on records obtained with receivers spaced more than 10 km apart. Occasional chance coincidences of fluctuations will, of course, occur, but even a single long record of good correlation would not be explainable in terms of the usual ionospheric scintillation theory, which assumes diffracting clouds with sizes less than 10 km.

While the ionosphere may be blamed for slow modulation of the relative amplitudes of the storms' substructure, the time of arrival of the rapid components should be unchanged. Gardner's and Shain's [20] failure to observe correlation of L pulses over a 25-km baseline is thus remarkable, requiring the ionospheric scintillation rate to be of an order of magnitude faster than hitherto believed. Their conclusion, in fact, was that the L pulses were real, and that only the longer time fluctuations could be explained by the ionosphere; this also was pointed out by Gallet [44].

Smith, *et al.*, [34], have compared records obtained in Florida and Chile, finding occasional correlated L pulses, together with evidence of ionospheric scintillation. In their conclusion, the remarkable fact of even a few correlations was noted as evidence of the Jovian origin of the L pulses.

A systematic spaced receiver program at the Yale Observatory [12], [46], [47], [58], [79] has produced a number of observations with receivers at 30 and 100-km spacings in which perfect correlation of storm substructure was present for the entire duration of the

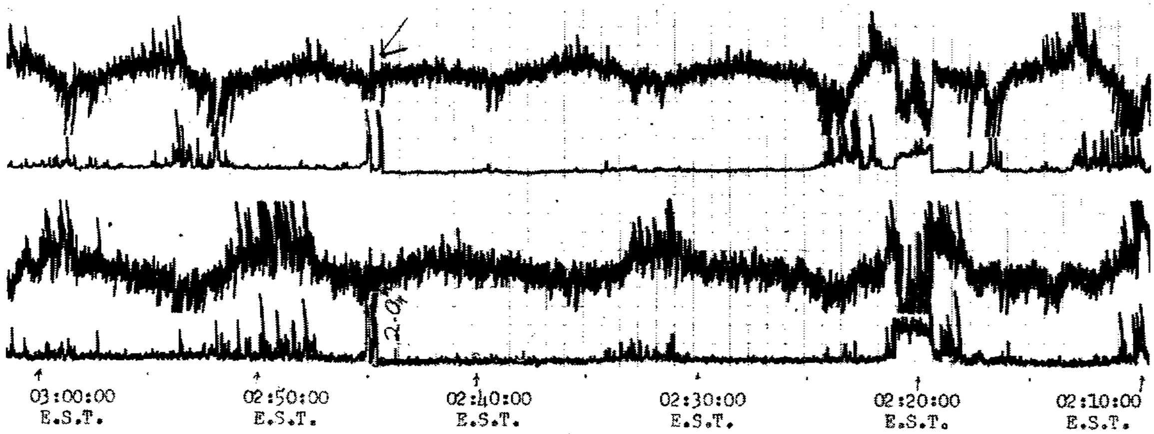


Fig. 4—Lobe-sweeping interferometer records of the Jupiter storm of July 28, 1963, obtained at the Bethany Observing Station of the Yale Observatory. Traces from top to bottom: 20 Mc phase, 20 Mc amplitude, 22.2 Mc phase, 22.2 Mc ampltitude.

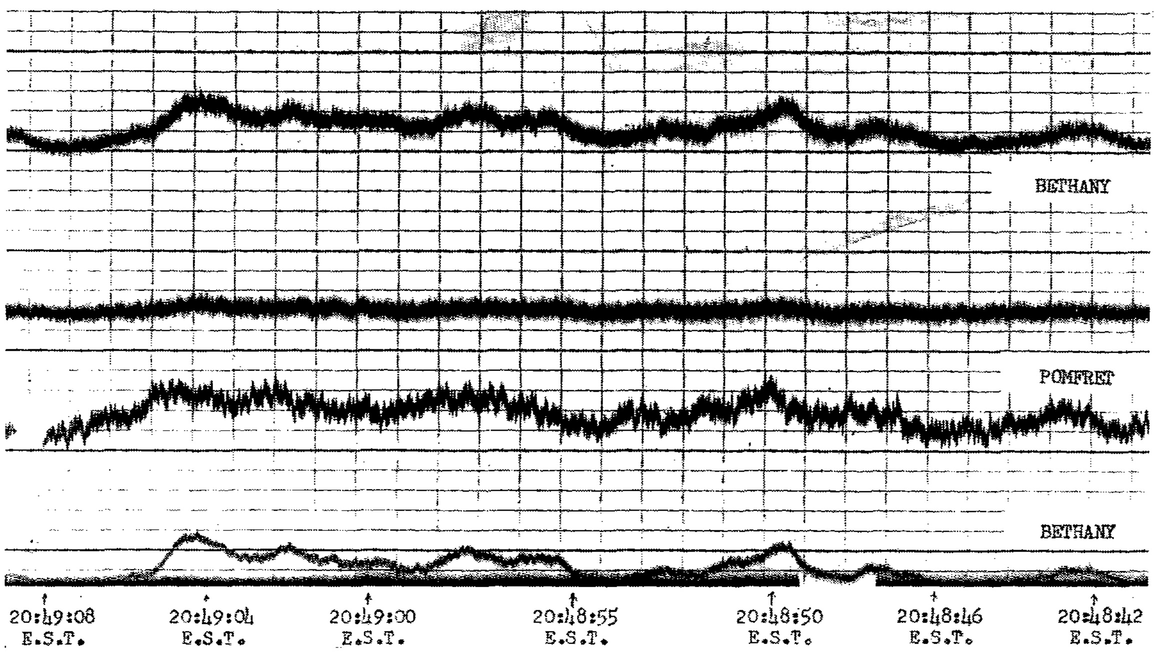


Fig. 5—22.2 Mc Jupiter L pulses, November 1, 1963. Bethany and Pomfret are 100 km apart on an ENE line; note the delayed arrival of the pulses at Pomfret.

storm. A portion of one such record is reproduced in Fig. 3. Note the good time correlation of burst group structure in Fig. 3(a), even though conventional ionospheric scintillation modulates the relative amplitudes of successive burst groups. The perfect envelope correlation of the L and S pulses received at three sites seen at high speed in Fig. 3(b) continued throughout the period of activity. A simple interpretation is that ordinary ionospheric scintillation acts only as a rather slow modulation on a pre-existing time structure incident on the top of the ionosphere.

The Yale group has found that L pulses may display all degrees of correlation from the perfect case shown in Fig. 3(b) to a total lack of correlation. In many cases where envelope correlation is sufficiently good to permit recognition of equivalent events on two channels, a systematic time lag is seen. The lag, which on different records may be anything from 0^s to $\pm 1^s$, remains constant for many minutes during a particular storm. Fig. 5 illustrates a particularly striking case with a lag of approximately $\frac{1}{2}$ sec, the western station receiving the signal first. This perfect envelope correlation with $\frac{1}{2}$ sec lag lasted for 15 minutes. The observed sense of the lag seems to reverse at opposition; this led Smith [47] to suggest an origin of the L pulses in a diffraction process by interplanetary electron clouds, whose systematic drift velocity perpendicular to the Earth-Jupiter line might be expected to change near opposition. Recent observations at Yale [79] have suggested drift velocities for the hypothetical diffraction pattern cast on the earth of 200–500 km/sec, and a pattern scale of the order of 1 km. Clouds at 1 astronomical unit capable of producing such a pattern would subtend an angle much smaller than that of a discrete radio source, but probably larger than Jupiter's decametric source (see Section V below), thereby explaining the failure to see L pulses on such objects as the Crab Nebula. This suggestion is being investigated both experimentally and theoretically; should it prove correct, Jupiter and quasi-stellar sources could serve as valuable tools in studying interplanetary cloud dynamics.

Storms containing S pulses are comparatively infrequent, and usually display perfect S pulse correlation over a 100-km baseline. A few records have been obtained, however, in which no correlation whatever is present. Furthermore, one solar outburst has been recorded on the same day as a Jupiter storm with S pulses; the solar radiation was found to contain S pulses, which were also perfectly correlated. It is concluded that the S-pulses are produced by some kind of propagation phenomenon not sensitive to source angular size, which usually is perfectly correlated over 100 km.

C. *Dynamic Spectra of Pulses*

In 1960, dynamic spectrum analyzers went into operation at the High Altitude Observatory (HAO) (15–34 Mc), University of Florida (4 Mc bandwidth at 18 Mc) and Yale University Observatory (1 Mc bandwidth at 22 Mc); the Yale and Florida instruments were particularly designed for study of the L and S pulses.

L pulses were found to occur simultaneously over bandwidths up to 9 Mc, and Warwick [60] reports a rough correlation between the duration of the pulse and the bandwidth on at least one record. The HAO dynamic spectrum analyzer can measure position as well as spectrum. Based on its records, Warwick [60] has reported a correlation between apparent shifts in Jupiter's radio position in the sky and the occurrences of L pulses, suggesting a common, non-Jovian origin for both phenomena. Thus, two lines of evidence, spaced-receiver observations and position-fluctuation correlation, suggest that the S and L pulses in the decametric radiation are due to hitherto undetected propagation effects.

The broad-band L pulses were found on closer examination to possess a fine-structure in frequency [36], [38], [42], [52], [65]; occasionally a pulse may be invisible at a frequency flanked 100 kc on either side by strong activity. The Florida group reports that this fine structure occasionally takes the form of a periodic structure in frequency, suggestive of harmonics. Further observations are needed to distinguish between two possibilities: 1) the propagation effect producing L pulses is frequency-sensitive, thereby creating the apparent fine frequency structure as well as the time structure, or 2) the radiation leaving Jupiter possesses the fine structure in frequency with only the time structure being imposed by propagation effects. Dynamic spectra of the S pulses have been reported by Smith, *et al.*, [65] to have a periodic structure in frequency as well, but with a tendency to drift to lower frequencies at 100 kc per second. Here also, further observations are required to determine the origin of the frequency structure.

IV. Occurrence Probability

The sporadic appearance of noise storms suggests the operation of a random process, whose annual, monthly or daily average occurrence probability may be estimated by dividing the time interval in which noise storms were recorded by the total time interval during which noise storms would have been recorded, if present. In a similar way, the average occurrence probability for a given longitude range of the central meridian of Jupiter may be calculated, since over a period of months that range is observed many times. Shain's [6] original occurrence frequency histogram, Fig. 2, may be transformed to an occurrence probability histogram if one has the additional information of the number of times a given longitude region was observed. However, the occurrence probability at a given instant of time may not be estimated with accuracy; that instant is observed only once and the resultant probability will be either zero or one.

Occurrence probability is thus useful in describing aggregates of data, and such descriptions may permit a choice among several simple but physically plausible statistical models.

A. *Statistical Models*

The simplest statistical model of this sporadic source would assume it to be a random process with a probability of occurrence $p_0(t) = \text{constant}$. If this hypothesis were true, no matter how one subdivides the data, estimation of occurrence probability should give the same result. That this is not the case is one of the most significant facts about the decametric emission; Shain's [6] finding of a greatly enhanced occurrence probability when a particular 135° region of System II longitude faces the Earth necessitates rejection of this simplest model. The occurrence probability of the decametric radiation is at least approximately periodic: $p_0(t+nP) = p_0(t)$, $n = 1, 2, 3, \cdots$. While the periodicity could be intrinsic to the source and have nothing to do with the rotation of Jupiter, this does not seem plausible and we therefore consider only rotating statistical models. While it is hardly possible to enumerate all conceivable models, many physically plausible ones fall into three general classes:

1) *Isotropic Sources in Polar Regions:* Isotropically emitting sources of radiation are presumed to be near the surface of the planet, rotating with it. Earth receives radiation only when seen above the source's radio horizon. Since the declination of the earth seen from Jupiter is different from zero, the period of emission may range from zero to a complete Jupiter rotation depending on the declination of the earth and latitude

of the source. Because of ionospheric refraction, the frequency of observation will also be a factor. This type of model predicts a very strong correlation of occurrence probability and length of emission period with the declination of the earth seen from Jupiter.

2) *Directive Sources:* One or more sources rotate with Jupiter and emit a relatively narrow beam of radiation which is observed only when directed toward the earth. This model is unusually flexible until a detailed emission mechanism is specified; it may be accommodated to a wide range of possible observational results.

3) *Stimulated Sources:* Sources of emission have an intrinsically higher probability of activity when the earth is near the meridian of the source. Such a terrestrial influence upon Jovian affairs seems highly unlikely; however, as seen from Jupiter, the earth and sun are always in approximately the same direction ($\pm 11°$) so that the required stimulation may come from the sun. In this case, the periodicity present in the occurrence probability would be Jupiter's period relative to the sun rather than to the earth, and the central meridian longitude of maximum activity (as seen from earth) should increase systematically by 22° through the course of an apparition.

As will be seen, observations generally favor the second class of models; this may be due largely to its flexibility when contrasted with the concrete predictions made by the other two.

B. Rotation Period

A longitude system for Jupiter may be defined by stating the central meridian longitude at some instant in time (epoch) and the period with which the longitude system rotates. For any assumed period, an occurrence probability histogram for a set of observations may be calculated; Fig. 6 is such a histogram plotted on a polar diagram. If one were to alter the assumed period substantially, the assymetries present in the histogram would be washed out; obviously the more asymmetric histogram was calculated with a period near the period present in the observations.

Three methods for determining accurate rotation periods for the radio sources have been used by various workers. One method, used by Gallet [9], [13], [44], Burke and Franklin [18] and Franklin and Burke [25], and Carr and Smith, *et al.* [22], [42] was made possible by the long-time persistence of the main peak of the occurrence probability histogram when plotted in System II longitude. The peak persisted, but its longitude drifted. The rate of drift is proportional to the error in the period assumed for calculating the histograms; calculation of the true period is trivial once the slope of the drift line has been established. The histogram drift technique is easily applied; drawbacks are its failure to use all the information present in the histograms and the difficulty of assessing its accuracy.

A second technique, used by Gardner and Shain [20],

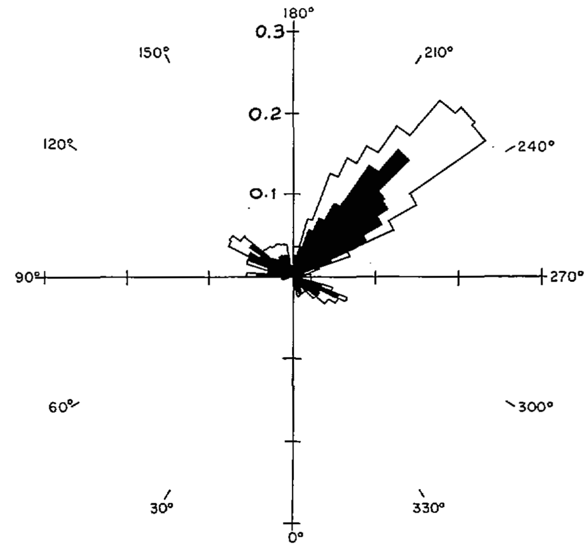


Fig. 6—1961 22.2 Mc data reduced to occurrence probabilities and plotted as a circular histogram to enhance the longitude symmetries and tri-lobed character of the emission at this frequency. Graduations of the principle axes are units of 0.1 in occurrence probability. Open histogram includes weak continuum events. (From Douglas and Smith, [69].)

involves a least-squares fit of the best drift line to a figure such as those in Fig. 1. This method is nonsubjective but also does not seem to make full use of the available information.

A third technique was introduced by Douglas [38], in which the variance of the histogram was calculated for a sequence of assumed periods. The peak of the plot of variance vs assumed period (Whittaker periodogram, [83], see Fig. 8) was shown to be an unbiased estimator of the period present in the data; furthermore, it can be shown that this procedure uses all the periodic information present in arriving at a period estimate. The entire process is quite free from subjective involvement, the accuracy of the result may be calculated, and with electronic computers, calculations are quite rapid. All period-determination techniques give equivalent results if the periodicity present is constant; if the period varies, the estimate may be averaged in different ways.

Period determinations have been published by Shain [6], Gallet [13], Burke [18], Gardner and Shain [20], Carr, *et al.*, [22], [42], Douglas [35], [38], [53], and Warwick [60]. The most extensive work was that of Douglas, who used observations furnished by all previous observers to obtain a mean period and standard deviation. A subcommission of IAU Commission 40 recommended in 1962 [48] that radio observations be referred to the longitude system designated System III (1957.0), defined as follows:

System III(1957.0)

Epoch: 1957 January 1.0 UT (JD 243 5839.5)
Period: $9^h55^m29^s.37$
Central meridian longitude at epoch: 108°.02.

For any time t expressed in Julian days, the longitude of central meridian of System III(1957.0), λ_{III}, may be obtained from the longitude of the central meridian of System II, λ_{II} (as tabulated in the various national ephemerides), from the relation

$$\lambda_{III}(1957.0) = \lambda_{II} + 0{:}2743(t - 243\ 5839.5).$$

C. Changes in Rotation Period

The System III(1957.0) period discussed in the previous section represents an average period over the interval 1950–60; small yearly fluctuations certainly can have gone unnoticed. Douglas [38] reports an upper limit to yearly period fluctuations of ± 2 sec, and an upper limit to a slow, monotonic change over the interval of 0.5 sec. Gallet [44], using the histogram drift technique, found the rotation period between 1956–57 to be 1 sec longer than the period between 1950–56. The significance of this result leans heavily on the accuracy with which the observed peak of the occurrence probability histogram mirrors the location of the true peak. For a small number of observations, sampling fluctuations are clearly possible; this is discussed more fully below. The 1-sec lengthening reported corresponds to a 12° change in longitude of the peak of the histogram; this lengthening, while entirely possible, does not seem to be statistically proven.

Douglas and Smith [73] found clearcut evidence for a change in Jupiter's apparent rotation period sometime between 1961 and 1962. Fig. 7 shows the occurrence frequency histograms obtained, displaying a systematic drift of the major peak with respect to System III(1957.0). Fig. 8 shows the periodograms for the 1950–61 and the 1961–63 intervals on the same scale; the $0^{s}.8$ lengthening is visible here as well. It should be emphasized that this does not necessarily imply a change in the rotation period of the solid body of the planet. A variety of other explanations might be offered; for example, the longitude of the main source of emission may have changed.

Warwick's [84] period determinations by the landmark method (see Section VI below) for the same period show no apparent deviation from the System III period; this must be regarded as an opportunity to learn something about the source rather than as a contradiction; the two period determination techniques are based on observations of different but presumably related things.

D. Longitude Profile

The longitude profile plotted in polar coordinates in Fig. 6 was obtained by calculating the occurrence probability in 5° intervals of System III(1957.0) from 22.2 Mc data obtained during the 1961 observation. The presence of three regions of enhanced emission is striking: Region 1, centered around 120°; Region 2, centered near 225°; and Region 3, centered 180° away from Region 1 at about 300°. Equally remarkable is the virtual absence of radiation in the quadrant 350°–80°. Smith *et al.* [52] have suggested that Region 1 is in fact double; the fact that its breadth is greater than that of Region 3 is certainly striking in most observational material.

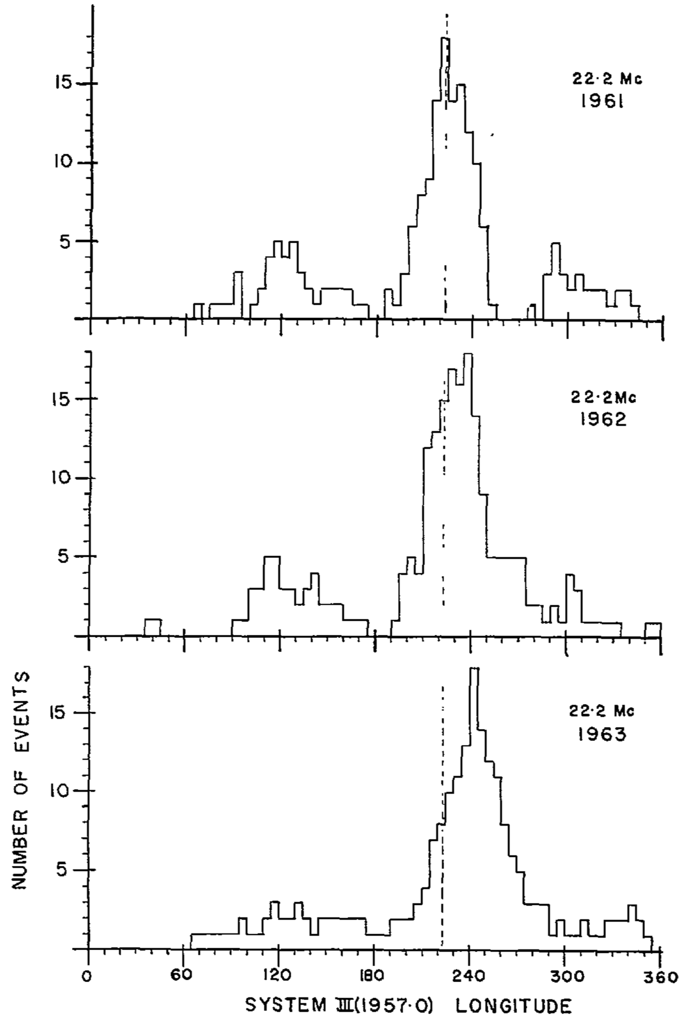


Fig. 7—Occurrence frequency histograms of Yale observations indicating change in apparent rotation period of the radio sources. The ordinate is number of events on all three histograms.

The overall appearance of the longitude profile resembles that of an antenna directivity pattern, with a main lobe, side lobes, and unusually good front-to-back ratio. It should be emphasized at this point that what is plotted is occurrence probability vs longitude, not strength of storms. Furthermore, the fact that peak occurrence probability occurs at approximately 225°, System III(1957.0), does not imply that the source is on the central meridian at that time; nor does the presence of three peaks imply the existence of three sources. Several alternative suggestions were proposed by Douglas and Smith [69], as suggested in Fig. 9.

It is a difficult matter to assess the accuracy of published longitude profiles. Each point is essentially an

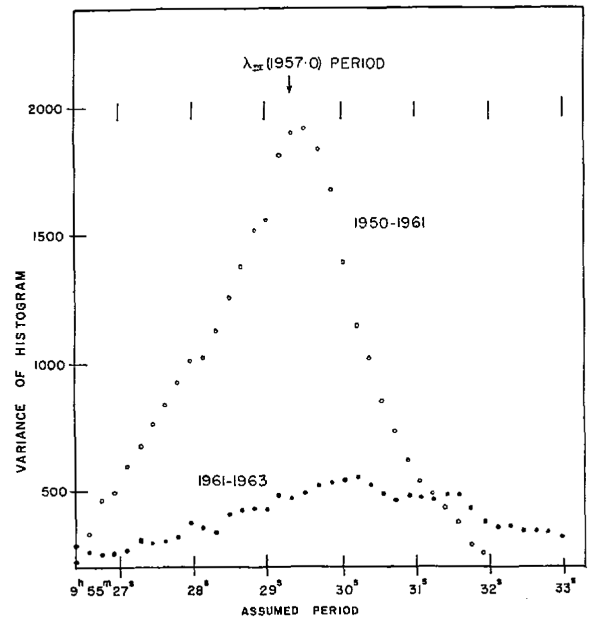


Fig. 8—Periodogram for the same observations as used in Fig. 7, showing the 0^s.8 lengthening in rotation period.

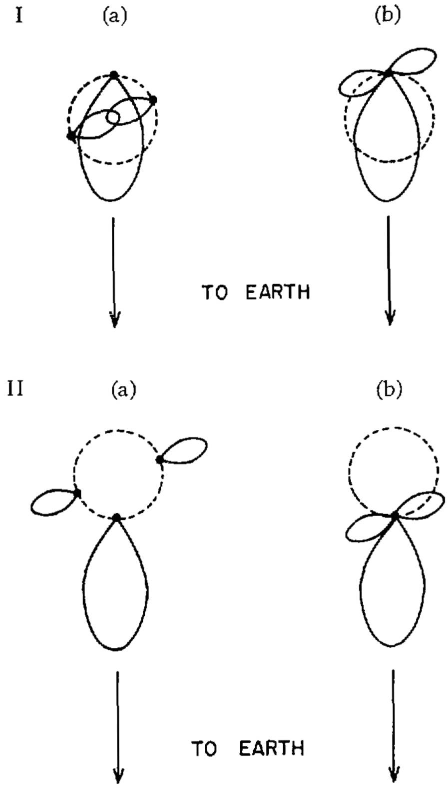


Fig. 9—Several possible radiation-cone configurations consistent with the occurrence probability histogram of Fig. 6, all drawn for the phase when the Region 2 cone is centered on the earth. The dotted circles represent Jupiter; the heavy points, emission regions. (From Douglas and Smith, [69].)

estimate of an occurrence probability at that longitude, given by the ratio of the number of events (N) to the number of observations (M): $p_{est}(\lambda) = N/M$. If the observations are considered to be statistically independent, the standard deviation of the estimate will be $\sigma = (p_{est}(1-p_{est})/M)^{1/2}$. For p_{est} small, the percentage error in p_{est} will be approximately $N^{-1/2}$. Thus, if the estimate of a point on the longitude profile is based on only four observed storms, a ± 50 per cent standard deviation in the estimate is expected. If the observations are not statistically independent, the standard deviation will be even greater. Furthermore, since most Jupiter storms are longer than 15° longitude of System III(1957.0) the estimates of occurrence probability at adjacent longitudes will covary: if one 5° interval has an unusually high value as a result of sampling fluctuations, the adjacent intervals will also be raised. Thus, the standard deviation expression given should be regarded as a minimum, and statements about small features of the longitude profiles must be made with caution.

A systematic bias may creep into longitude profile shapes obtained with different instruments if the shape is a function of the limiting flux to which Jupiter storms may be detected. The open histogram in Fig. 6 is the result of adding a substantial number of order-of-magnitude weaker continuum storms to the observations of the main phases of the emission; no systematic change in shape is evident. If this insensitivity to strength of storms has held through the years, data from many observers obtained at the same frequency may be compared, making up in part for the lack of a long, homogeneous series of records.

E. Correlation of Longitude Profile with Frequency

Three kinds of frequency correlations in the longitude profiles were noted by early observers: the occurrence probability and width of the major peak increased with decreasing frequency; and the longitude of the major peak increased slightly with decreasing frequency. In recent years, low frequency observations in Florida and Chile [42] and those of Ellis [49] in Tasmania have extended these results. Although thorough statistical discussions in the literature are lacking, the trends, if significant, may be of great importance in interpreting the emission mechanism. Ellis' observations at 4.8 Mc show that the shape of the longitude profile has changed substantially, with only two principle sources being visible at this frequency. Fig. 10 illustrates Ellis results; the occurrence probability is practically constant, but the mean power is concentrated in two major regions and varies almost sinusoidally.

Observations of the longitude and width of the Region 2 peak are plotted vs wavelength in Fig. 11. All points are from Carr, *et al.*, [42] except the points at 4.8 Mc ($\simeq$60 m), which are estimated from Fig. 9 (Ellis [49]). The shift and broadening is clearly evident (Ellis, [49], [56], [66], and Ellis and McCullough, [68], [75],

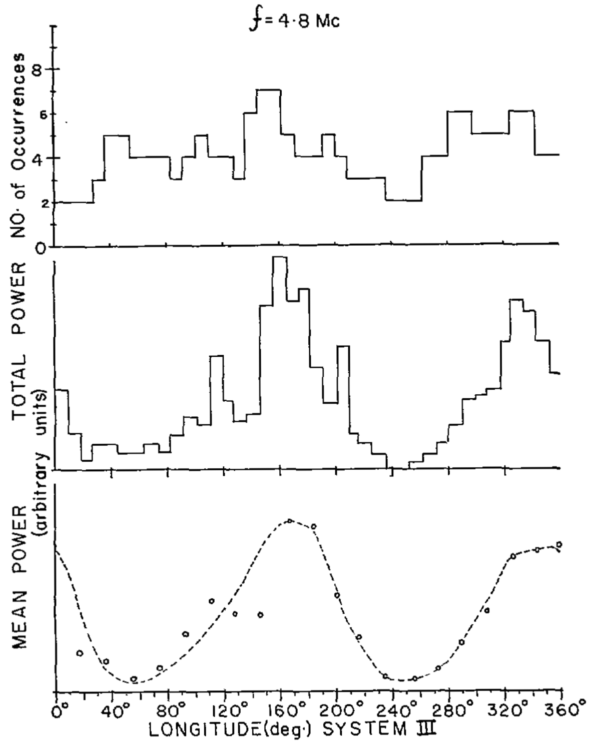


Fig. 10—Number of occurrences, total power and mean power as a function of System III(1957.0) longitude. (From Ellis and McCullough, [68].)

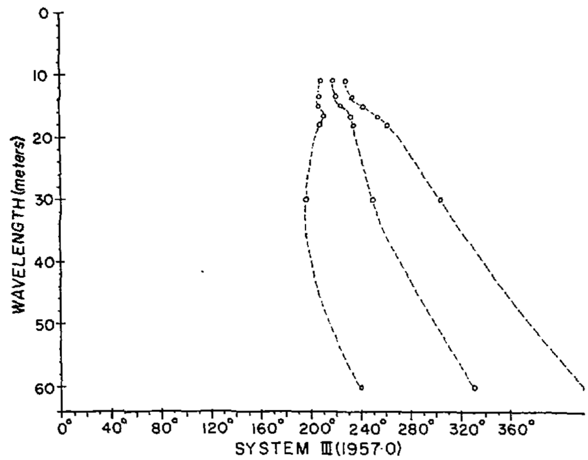


Fig. 11—Longitude of peak probability (center line) and ½-peak probability (outer lines) of the Region 2 peak as a function of wavelength.

Smith, *et al.* [80]). Extension of observations to the vacant intermediate wavelengths as seen in Fig. 11 and thorough statistical discussion of the results is one of the more pressing observational tasks confronting observers. Particularly intriguing is the suggestion by Ellis and McCullough that the source mechanism displays itself most characteristically at very low frequencies, the high-frequency behavior being understandable as the result of perturbations.

F. Correlation of Longitude Profile with Time

A prominent characteristic of the longitude profile is its relative persistence in shape over long periods of time. The amplitude of the occurrence probability is a strong long-term function of time, which some observers have interpreted as an effect of solar activity. However, the fortuitous near coincidence of Jupiter's revolution period (11.86 years) with the sun-spot cycle (11.1 years) makes it very difficult to distinguish effects that are due to Jupiter's position in its orbit and those due to mean solar activity. Estimates of peak Region 2 occurrence probability at 22.2 Mc for each year in which observations are available, are plotted in Fig. 12 against three plausible potentially-correlated functions: provisional sunspot number, solar latitude of the line joining the sun and Jupiter [52], and the declination of the earth as seen from Jupiter. If one makes suitable shifts in phase, any of the three functions may be brought into approximate correlation. A correlation with the first two might reflect any influence of the general activity of the sun on Jupiter or on propagation conditions in the interplanetary medium; a correlation with the third would be expected with models of class 1) or 2) of Section IV, A. Unfortunately, a thorough statistical consideration of the significance of these possible correlations is not yet available.

In addition to the possible inverse correlation with mean solar activity, Warwick [37], [40], [45], [60] finds evidence for an association of periods of Jupiter activity with periods of solar continuum in 1960 and 1961. Such a correlation, if well established, could be a most significant indicator of the type of emission mechanism responsible for the decametric radiation. Douglas [38] failed to find a significant correlation in the records on 1960; the effect was present but explainable as sampling fluctuation when the tendency of Jupiter activity to last several days was recognized. Carr, *et al.*, [39], [42] suggest a correlation of Jupiter emission with geomagnetic A index with an 8-day lag; once again the numbers are small and a significance check is lacking.

G. Intrinsic Duration of Emission

No definitive conclusions regarding the relaxation time of the source may yet be reached, but several limiting statements may be made based on statistical investigations by Douglas [38], [53], [58]. First, it is found that the three emission regions are significantly correlated, and must be connected by a common directivity or stimulation process, or perhaps represent the same source viewed from different directions. Second, observation of a Jupiter storm greatly enhances the probability that activity will be seen at the same longitude one rotation later. Quantitative work is made difficult by the sampling periodicity imposed by the earth's rotation; however, it is clear that the limitation of storm duration to tens of minutes is not a result of commencement and cessation of the general activity

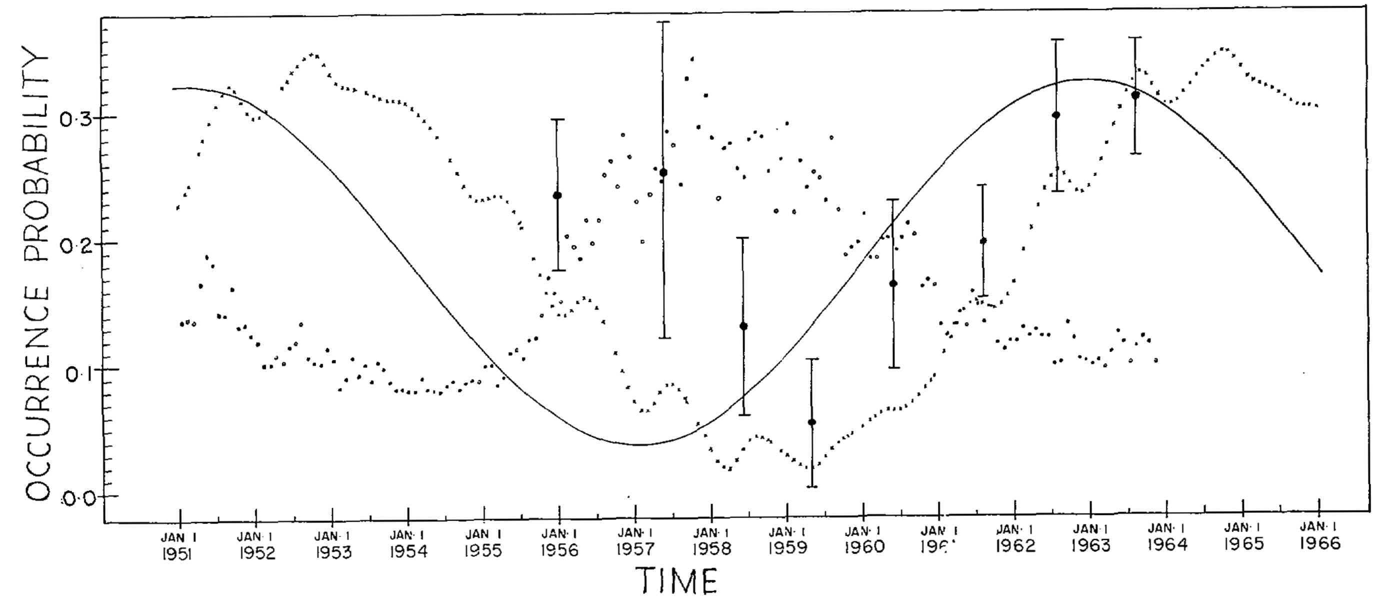


Fig. 12—22.2 Mc Region 2 occurrence probability (heavy dots with error flags) compared with provisional sun-spot number (open circles). Also shown (without ordinate scales) are declination of earth seen from Jupiter (x's) and sub-Jovian latitude on the sun (line). Range of sub-Jovian latitude on the sun is about ±9°; range of declination of earth is about ±3°.

period. A Jupiter activity period generally lasts more than two days, and frequently more than five days. It is interesting to speculate that even the eventual apparent termination of the activity period after five days or so is the result of a shift of emission directivity out of the plane containing the earth; a random tendency of this sort might also produce a correlation of occurrence probability with declination of the earth as seen from Jupiter.

V. Angular Size of Source

Slee and Higgins [86] successfully observed Jupiter with an interferometer having a baseline of 1940 wavelengths at 19.7 Mc (32.3 km). The fringe visibility of the radiation was not reduced at this baseline, giving an upper limit to its angular size of one third the diameter of the planet. This observation confirms the suggestion of many observers that the source has small angular size; we have seen in Section III above that this has relevance in unexpected ways to interpretations of the emission.

VI. Dynamic Spectra of Noise Storms

The HAO radio spectrograph, a swept-frequency phase switching interferometer, has produced an impressive collection of dynamic spectra of noise storms in the 7.6 to 41 Mc range. Fig. 13 shows the appearance of a Jupiter noise storm on this instrument. This storm, which occurred when Region 2 was facing the earth, is seen to drift lower in frequency with time. Such drifts are characteristic of emission from this region; the opposite sense is observed when the emission occurs with Region 1 facing the earth. Warwick [60] has found that a number of characteristic shapes in the frequency-time plane are reproduced repeatedly; drawing an analogy with optical features of a planet, he calls them landmarks, and suggests that Jupiter possesses a more or less permanent set of landmarks, *i.e.*, a permanent dynamic spectrum.

The time of occurrence of a distinguishable part of such a landmark can be determined with considerable precision. Fig. 14 is a plot of central meridian longitude corresponding to time of landmark occurrence vs time in days from opposition. Several remarkable properties of this diagram were pointed out by Warwick [60]. First, the fact that the landmark is only observed within about ±9° of System III(1957.0) longitude implies a very narrow beaming of the radiation. Second, the Region 2 landmark shows no systematic drift with time. If the landmarks were the result of pure solar stimulation (model 3), a systematic drift of 22° would be expected. A repetition of this observed lack of drift in several more apparitions would be sufficient to rule out this kind of model. Third, it is very curious that the Region 1 source shows just the sort of systematic drift that the class (3) model requires, but in the wrong sense. Such a systematic change in longitude would serve to broaden Region 1 on occurrence-probability histograms; such a broadening has already been mentioned. Warwick's observations of the drift of the landmark in this region provides an alternative explanation to the double source suggested by Smith, *et al.* [52].

Warwick has used the rate of drift in longitude of the Region 2 landmark to determine a rotation period for the source in a method similar to the histogram-drift technique used by other observers. The smaller width of the landmark emission cone has permitted more accurate period determination in a given length of time.

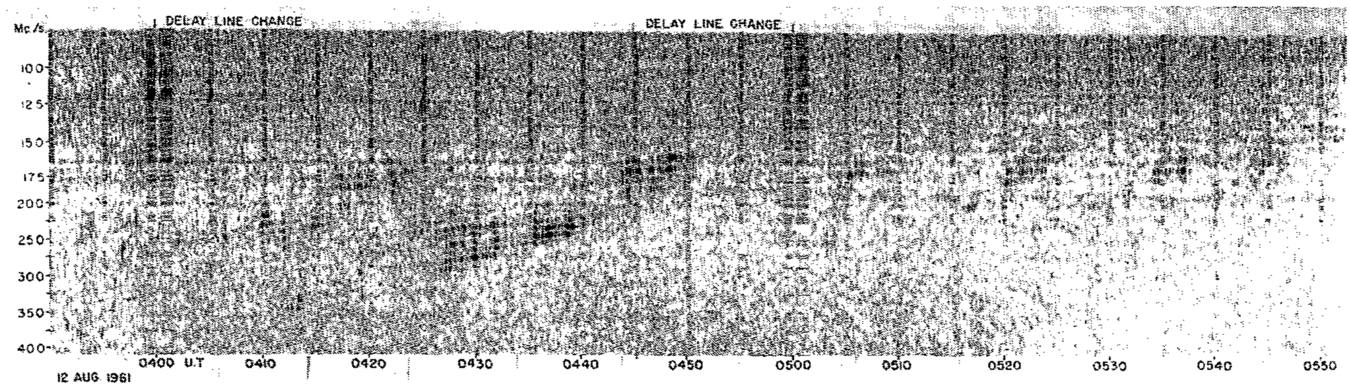


Fig. 13—Region 2 radiation seen on the HAO swept-frequency interferometer. Note the drift of emission from high to low frequencies. (From Warwick, [60].)

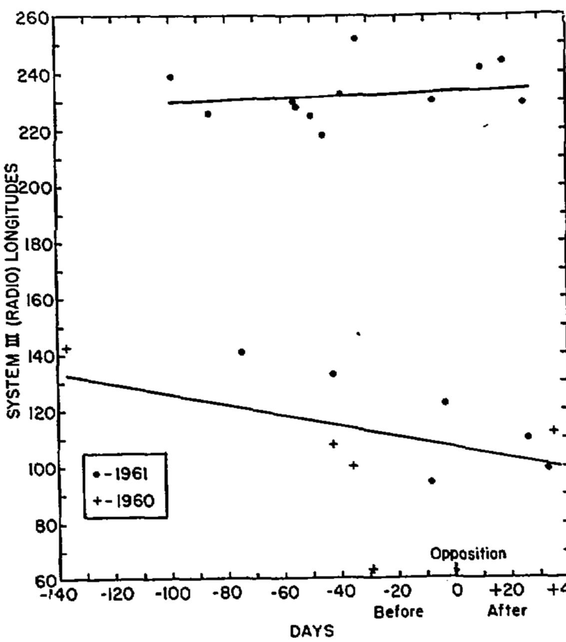


Fig. 14—Central meridian longitude at landmark occurrence as a function of days from opposition. The scatter of points is real, not a result of inaccuracy in estimation of time of landmark occurrence. (From J. W. Warwick, [60].)

VII. Polarization

The general predominance of the right-hand sense of polarization of the decameter radiation near 20 Mc has been confirmed by several observers [42], [51], [69]; multi-frequency polarization observations have been made by Sherrill at Southwest Research Institute, [74] and by Barrow at Florida State University [82]; and observations at 10 Mc by Dowden at the University of Tasmania [76].

Left-hand polarization is seen with increasing frequency at longer wavelengths; at 16 Mc, one third of the activity is in the left-hand sense. Dowden reports that left-hand polarization at 10 Mc is primarily concentrated in emissions from Region 1; Sherrill and Barrow have both noted a tendency for Region 1 polarization to differ significantly from that of Region 2.

Interpretation of polarization records is complicated by many equipment calibration problems, together with the apparent presence of propagation phenomena capable of differentially attentuating the two characteristic modes and producing rapid (less than one minute) fluctuations in the apparent axial ratio of the radiation. Longer term systematic effects are also apparent in the records: several observers have noted a change from right hand to left hand and back again in a ten minute period at 22.2 Mc.

Even if solutions to the equipment and ionosphere problems were known, the interplanetary medium would be optically active: the electron clouds and interplanetary magnetic field will produce Faraday rotation. A more important obstacle to straightforward interpretation of polarization records is the mechanism recently proposed by Lusignan [77], [81]. Relativistic effects in the solar wind will cause it to possess linear characteristic modes, which will change the axial ratio and sense of polarization of the radiation rather than simply rotating it. This phenomenon can prove exceedingly valuable in permitting a study of the properties of the continuous solar wind using Jupiter as a probe.

VIII. Flux

Absolute measurement of the decametric flux is made difficult by several circumstances: one must use an antenna of known gain with a power-linear receiver whose output is integrated over a period long compared to the duration of ionospheric and interplanetary diffraction shadows. The resulting measurement must be corrected for the ionospheric absorption present, and the whole process must be done simultaneously in two orthogonal polarizations. With these precautions, a mean flux measurement at one frequency could probably be made to an accuracy of 10 per cent or so; such observations are not available at any frequency. Even many of the order of magnitude estimates in the literature are open to question on one or more of the above grounds, particularly those made at frequencies below 15 Mc (5 Mc flux reported by different observers covers a range of 100). At this time, it seems safe to say only that average flux near 20 Mc can be on the order of 10^{-21} wm^{-2} c^{-1}, and that the flux increases with increasing wavelength down to 10 Mc. Filling in this picture is a very important observational problem.

The decametric power radiated by Jupiter establishes the radio energy requirement; its calculation requires knowledge of 1) intrinsic time structure of the source, 2) instantaneous bandwidth of radiation, 3) spectrum, 4) flux, and 5) size of directivity cone. The results are particularly sensitive to items 3) and 5), and quoted figures range from 2×10^7 to 7×10^{11} w. The author is much inclined to favor the first of these figures, given by Warwick [60] and based upon a small ($\pm9°$) emission cone, which seems quite reasonably well established by the dynamic spectrum observations, and using average rather than peak flux values. Residual uncertainty must still be of an order of magnitude. Further progress must await more information on each of the five contributing points above, particularly time structure and flux.

IX. Conclusion

The following reasonably well established observational characteristics of the decametric radiation from Jupiter may be noted: 1) Decametric radiation is due to one or more sources having angular size less than one third the planet's disk; very probably much less. 2) The source is active for a period of days; the hypothesis of a continuously active source is not disproved. 3) General probability of source activity is a slow function of time, with a cycle on the order of ten to twelve years; it is not definitely established as an inverse correlation with the sun-spot cycle. 4) There is a tendency for positive correlation with solar continuum activity suggested but it is not as yet unambiguously established by the data. 5) Rotation period was well established between 1950 and 1961; the change in period or drift in longitude of major peak, between 1961 and 1963. 6) There are three obvious peaks of occurrence probability in the longitude profile; a broadening of the Region 1 peak is probably due to an elongation effect rather than a fourth peak. 7) The Region 2 peak is later in longitude and broader at lower frequencies; the shape of the longitude profile changes significantly at lower frequencies. 8) A permanent dynamic spectrum exists. 9) "Landmark" radiation is apparently beamed in a very narrow ($\pm9°$) cone. 10) The radiation is polarized; and is predominantly righthand near 20 Mc, with an increasing percentage of lefthand at lower frequencies; there is a suggestion of correlation of polarization ellipticity, or sense, with longitude. 11) Decametric power is probably emitted at 10^7 to 10^8 w averaged over long periods of time.

Many authors have proposed theories of the decametric emission capable of explaining some of the observational features listed above; at the present time, no one theory is generally accepted. A transition has occurred, however, from one type of theory to another. In early work, plasma oscillations were frequently invoked [23], which explained both the narrow-band characteristics of the emission and the burst-like structure. In theories not dealing specifically with the emission mechanism, the sources were generally regarded as being beneath a Jovian ionosphere, on the surface of the planet [6], [8], [10]–[13], [24], [31], [32], [36], [45]; directional properties were produced as propagation effects in the Jovian ionosphere. Now, stimulated by the discovery of Van Allen belts around Jupiter [64] and by the observations and theories of Warwick [37], [42], [43], [60], [65], theories center around mechanisms operating in the upper atmosphere of the planet at the gyrofrequency, producing directive radiation that is intrinsically polarized [43], [52], [53], [57], [60], [61], [67], [69], [70].

Theory and observations are unfortunately difficult to compare in many areas, primarily because of the great complexity of the observational problem. Perhaps the best correlations of the two occur in the theory and dynamic spectral work of Warwick, and in the theory and longitude-profile work of Ellis. Clarification of the observational picture requires a simultaneous study of all phenomena, in order to distinguish intrinsic and propagation-induced properties of the radiation. Particular attention should be given to the several octaves below 20 Mc, a region of great potential importance which is not as yet adequately explored.

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Radio Telescopes

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Summary—A radio telescope is used in radio astronomy to measure the intensity of the radiation received from various parts of the sky. Such a telescope must be able both to detect and to locate faint radio sources of small angular size, and also to measure the brightness distribution across extended radio sources or over large sky areas. Ideally the telescope should be capable of making such measurements over a wide frequency range and for different types of polarization of the incoming waves.

The noise powers available in radio astronomy are very small, and some of the radio sources have angular sizes or angular structure of, perhaps, only one second of arc, so that a radio telescope needs both high gain and good resolving power. The paper describes various types of radio telescopes which have been built and tested, and outlines the astronomical needs which they fulfill.

The parabolic reflector antenna is first described, with particular reference to the fully steerable 210-foot telescope at the Australian National Radio Astronomy Observatory and to the 300-foot transit telescope at the U. S. National Radio Astronomy Observatory. Of the telescopes which use fixed or partly fixed reflector surfaces, those at the University of Illinois, at the Nançay station of the Paris Observatory, and at the Arecibo Ionospheric Observatory in Puerto Rico are described in some detail. Instruments in which the resolution is improved without a corresponding increase of collecting area, such as the cross-type antennas, are briefly described. The future progress of radio telescope design is certain to follow the development of parabolic dishes to still greater sizes, and the exploitation of synthetic antenna systems; the article concludes with a survey of both developments.

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I. The Astronomical Requirements

A RADIO TELESCOPE is used to study the radio waves received on earth from a variety of astronomical objects. Some of these may be well known from optical observations, but many others have been discovered only by radio astronomy. Within the solar system, the sun, moon and the nearer planets are all well-known radio sources. Beyond the solar system, but within our own galaxy, are many other radio sources, some of which are already identified with optically known objects such as the remnants of supernova explosions or clouds of ionized hydrogen gas. Within our galaxy, the neutral hydrogen gas radiates and absorbs the 21-cm line, and absorption by the OH radical at 18 cm has been detected. Beyond our galaxy, other galaxies have been studied by their radio emissions, both over a wide wavelength range and for some of the nearer galaxies, by observing their hydrogen-line emissions. Radio waves have been measured coming from objects so distant that in one case the optical red-shift represents an apparent recession velocity of more than 0.4 of the velocity of light. Measurements of the apparent angular size of radio sources indicate that some may have diameters of less than a second of arc.

It is thus clear that the astronomical requirements for a radio telescope may be so varied that no single design of instrument can possibly satisfy all the requirements.