1 September 1961, Volume 134, Number 3479 SCIENCE

CURRENT PROBLEMS IN RESEARCH

Radio Spectrum of Jupiter

Radio-frequency signals are providing important new information about the giant planet and its environs.

Alex. G. Smith

The noted scientist Vannevar Bush once said that there is no more thrilling experience for a man than to be able to say that he has learned something which no other person in the world ever knew before him. This remark was quoted by the young astronomer K. L. Franklin in describing his emotions when he and Bernard Burke accidentally discovered that Jupiter, the largest of the planets, was occasionally broadcasting powerful radio waves at a frequency of 22.2 megacycles per second (Mcy/sec).

The time was early 1955, and the two men were engaged in testing a large new receiving antenna or "radio telescope," which was to be used by the Carnegie Institution of Washington in making a radio map of the sky. At first annoyed by what seemed to be a strong, intermittent interference on many of their records, they suddenly realized that the "interference" always came precisely from the direction of Jupiter, and that it was even moving slowly among the stars at the same rate as the planet. This totally unexpected discovery marked the first recognition of radio-frequency energy from a planet (*1, 2*).

Six years later, despite the great strides which have been made in radio astronomy, Jupiter still appears to be unique among the planets as a radio transmitter. Only the sun itself rivals the giant planet as a source of powerful outbursts in the short-wave bands of the radio spectrum. Additional interest has been lent to the problem by the recent discovery of remarkably high levels of microwave radiation, and it is probably safe to say that Jupiter is being investigated more intensively at the present time than it has been in any other period in history.

Low-Frequency Radiation

Immediately after their discovery of the 22.2-Mcy/sec radiation, Burke and Franklin re-examined records taken during the previous year with a smaller antenna at the same frequency and were able to recognize at least one instance of a strong Jovian outburst. Since a more sensitive 38.7-Mcy/sec antenna, which had been operating at the same time, failed to detect any radiation, they concluded that the sporadic radio noise is concentrated in the low-frequency region, below 38 Mcy/sec (*1*). We now know that this conclusion was correct, although in view of the highly erratic behavior of the outbursts it was based on rather scanty evidence.

Observations that my associates and I have made over a span of 5 years (*3–6*) have indicated that Jupiter has been most active at frequencies near 18 Mcy/sec, and only rarely has the radiation extended to frequencies as high as 28 Mcy/sec. In terms of the absolute energy received at the earth's surface, the Jovian bursts produce 18-Mcy/sec fluxes of as much as 10^{-19} watt per square meter per cycle per second of bandwidth, a level of energy about 200 times higher than that received from the most intense radio star. During 1960, with the help of a new field station in Chile, we were able to obtain extensive data over an unprecedented range of frequencies, and when these data were analyzed in terms of the fraction of the observing time during which radiation had been received at various frequencies, the curve shown in Fig. 1 resulted. The peaking of the activity near 18 Mcy/sec and the rapid fall-off at higher frequencies are evident. Less certain is the form of the curve below 16 Mcy/sec, because of the lack of data between 10 and 16.7 Mcy/sec and the possibility that the signals are partially absorbed by the terrestrial ionosphere at these low frequencies. During the current year we are making additional observations at 5 and at 15 Mcy/sec in an attempt to clarify this portion of the curve. These new observations should be aided by the fact that solar activity is declining rapidly from the record sunspot peak reached in early 1958, for past experience indicates that as the sun quiets down the terrestrial ionosphere becomes more transparent to radio waves of the lower frequencies (*7*).

As may be seen, the observer of the Jupiter outbursts is pretty well confined to the frequency range between a few megacycles per second and 30 Mcy/sec, by the opacity of the earth's ionosphere at the one extreme and by the absence of Jovian radiation beyond the other extreme. This part of the spectrum is one of very low frequency, by the usual standards of radio astronomy, and in many ways it is a difficult region in which to work. It lies athwart the crowded short-wave bands, so that inter-

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ference from radio stations is a serious problem. It also lies in a region of the spectrum in which natural static from thunderstorms is severe. Moreover, since the low-frequency waves are of long wavelength, antennas of reasonable size have poor directivity—that is, they accept signals from a relatively large area of the sky. In most of our work we have been employing simple fixed arrays of from 4 to 64 dipoles, together with rotatable Yagi antennas resembling over-sized television aerials. Since receiver noise is no problem at these frequencies, commercial shortwave receivers are used to amplify the signals, which are then permanently recorded on paper by ordinary pen recorders.

The ionosphere not only acts as a screen to shut out low-frequency signals from space but it also serves as a giant mirror to reflect interference from distant terrestrial thunderstorms and radio stations into the antennas. Because the ionosphere is formed by solar radiation, it begins to fade at sunset. Between midnight and dawn, conditions are generally the most favorable for low-frequency radio astronomy, and our best observations have been made during this period. It is possible that as the sunspot cycle wanes the useful observing hours can be extended considerably.

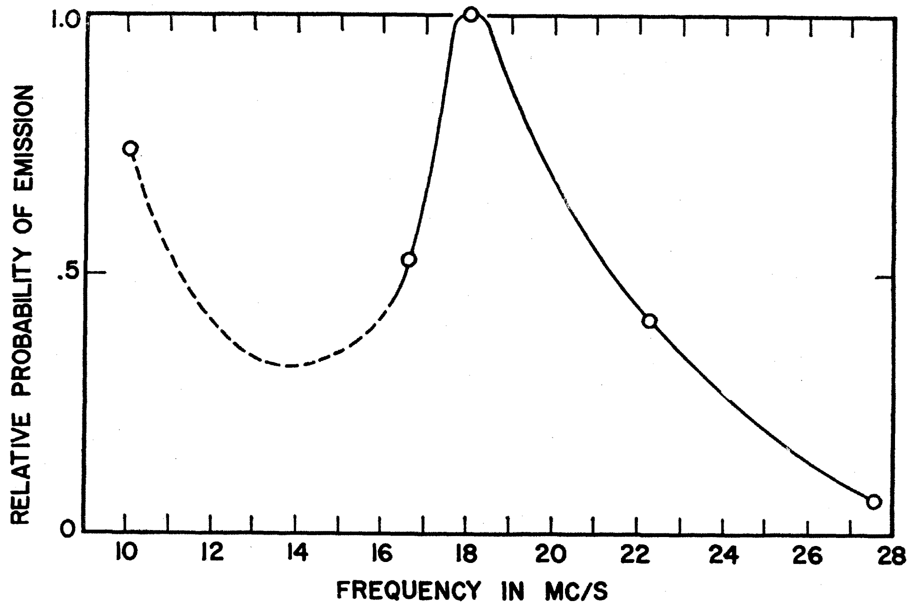

Fig. 1. A curve showing the relative probability of emission of radiation from Jupiter at various radio frequencies. This probability may be interpreted as the fraction of the total 1960 observing time during which radiation was actually received. The peak of the curve corresponds to an absolute probability of about 0.1—that is, 18-Mcy/sec signals were detected during approximately 10 percent of the observing time.

Localized Radiation Sources

As soon as he learned of the discovery of the Jovian radio outbursts, the Australian radio astronomer C. A. Shain began a search of an extensive series of records taken at 18.3 Mcy/sec in 1950 and 1951. Although these records had been made for the purpose of mapping the radio noise from the Milky Way, no less than 61 of them proved to contain disturbances which indicated by their positions that they were Jovian in origin [as in the case of Burke and Franklin's records, these signals originally had been dismissed as being due to terrestrial interference (*8*)]. Through this fortunate circumstance there immediately became available a large body of data which antedated the actual discovery by nearly 5 years. (The recovery of such pre-discovery data is not unusual in astronomy; for example, images of the planet Pluto were found on photographic plates exposed 11 years before astronomers knew of the planet's existence.)

Shain was able to show at once that there was a maximum probability of receiving radio radiation when one particular face of Jupiter was turned toward the earth as the larger planet rotated on its axis—a finding which suggested that the signals were coming from a localized source rather than from the planet as a whole. He further noted that the probability of hearing signals from this source was high only when the source was near the center of the visible disc—that is, "aimed" toward the earth. Shain speculated that this directional effect might be due to an electrified layer in the Jovian atmosphere above the source. Such an ionosphere would, as in the case of the earth, limit the escape of radio waves to a vertical cone, the angle of which would depend on the frequency of the radiation and on the electric charge density in the ionized layer.

Observations made in recent years have amply confirmed the conclusion that the radiation is from localized sources (*3–5*, *9–11*). To illustrate this point, Fig. 2 shows a histogram which summarizes the 18-Mcy/sec data of the University of Florida Radio Observatory for the year 1960. In this figure the probability of receiving radiation has been plotted as a function of the longitude of the center of the visible disc of Jupiter. It should be noted that because this visible "surface" is merely a shifting cloud mass, a purely arbitrary system of Jovian longitudes must be employed. Such systems have been established by imagining that 0 degrees of longitude was at the center of the disc at some specified instant, and that the system thereafter continued to rotate at a constant rate approximating the rotational speed of the planet itself. Since the equatorial clouds rotate appreciably faster than clouds in higher latitudes, optical astronomers have found it convenient to define separate longitude systems for keeping track of features in the two regions. "System I" rotates in $9^{h}50^{m}30^{s}.0$; this represents a kind of mean period for the equatorial clouds. "System II" has a period of $9^{h}55^{m}40^{s}.6$, keeping it approximately in step with markings in the temperate zones (*12*).

It is evident from Fig. 2 that radiation is received most frequently when longitudes near 240 degrees are turned toward the earth. There are also secondary probability peaks near 150 and 345 degrees, suggesting the presence of at least three radio sources on the planet. This same pattern of peaks tends to appear year after year, and in histograms plotted for a number of different frequencies, although in some cases the data have been too scanty for effective analysis. The figure shows clearly that the Jovian radio sources do not by any means emit continuously. Even the principal source, at 240 degrees, has a probability of emission of only a little over 0.3, indicating that in 1960 18-Mcy/sec signals were received only about one-third of the time when this source was turned toward the earth, and the probabilities at other frequencies were even lower (Fig. 1). Evidently the activity of the sources is highly sporadic. (There also appear to be year-to-year variations in the rate of emission. In 1957 and 1960, for example, Jovian radiation was relatively frequent and intense, while in 1958 and 1959 the planet was much less active.)

The directional characteristic which Shain noted is clearly demonstrated by the relative narrowness of the peaks in Fig. 2. If the sources radiated isotropically, each source could be heard as long as it was anywhere on the visible half of the planet, and each peak would extend over a full 180 degrees of longitude. It is, then, this directional property which permits one to resolve the individual sources, for otherwise the peaks would be so broad that all of them would merge together. The same kind of argument can be used to limit somewhat the possible latitudes of the sources, about which the radio data as yet give no direct information. Since the rotational axis of Jupiter is nearly perpendicular to the plane of the ecliptic, vertical radiation cones emitted by sources at high latitudes could never strike the earth.

Unfortunately for Shain's attractive ionospheric hypothesis, our data, as well as the data of other observers (*3, 5, 9, 10*), show that the widths of the peaks decrease as the frequency of the radiation increases (see Table 1). This behavior is in direct opposition to what one would expect if radiation from a source near the surface of the planet were being limited to a "cone of escape" by an ionosphere. At the present time, therefore, the directional characteristic of the sources must be classed as one of the unsolved problems.

Table 1. Angular extent of the principal source as a function of frequency. The source width was measured at the half-amplitude height of the peak on histograms such as that of Fig. 2 (University of Florida data for 1960).

Frequency (Mcy/sec)	Peak width (deg)
10	108
16.7	54
18	43
20	36
22.2	27
27.6	20

Rotation Period of Radio Sources

In his analysis of the 1950–51 records, Shain found that the radio outbursts tended to recur with a periodicity which closely matched the System II rotation period adopted by the optical astronomers. This not only led to the concept of a localized source but also suggested that the radio source was rotating at approximately the same rate as the cloud belts in Jupiter's temperate zones (*8*). Over an interval of months, however, the source seemed to show a steady decrease in its System II longitude, and Shain decided that it was rotating slightly faster than the longitude system. We now know that this conclusion was correct, although Shain's value of 28 seconds for the difference between the periods was excessive. Later evaluations (*3, 9, 10, 13*) placed the difference closer to 10 or 11 seconds, and a recent redetermination by our group, using data which now extend over a decade, has given a figure of $9^h55^m29^s.35$ for the rotation period of the radio sources (*5*). Since J. N. Douglas and H. J. Smith recently derived, by an independent method, a value which differs from ours by only 0.02 second (*11*), the period now seems to be established with high precision.

The radio sources appear to rotate at a constant rate year after year, in contrast to the optical markings, which show highly variable periods. The erratic behavior of the optical features is to be expected, since they are entirely atmospheric phenomena of the dense clouds which perpetually shroud the planet (Fig. 3). On the other hand, the regularity of rotation of the radio sources suggests that they may be connected with the physical surface of Jupiter, either directly or through the action of a magnetic field. The period of rotation of the radio sources may thus be the previously undetermined period of rotation of the solid planet itself.

Repeated attempts have been made to correlate the radio sources with optical features. Actually, the number of quasi-permanent optical markings is very limited. The famous Great Red Spot has probably been observed since 1664, and a group of three white spots, which are identified cryptically as *FA, BC,* and *DE,* has persisted since 1939 (*14*). At the time that Burke and Franklin discovered the radio signals, the principal radio source almost coincided in longitude with the Red Spot, but the two soon drifted apart. Shain pointed out (*8*) that in 1951 the radio source was at the same longitude as the spot *DE,* but again the rotation rates have

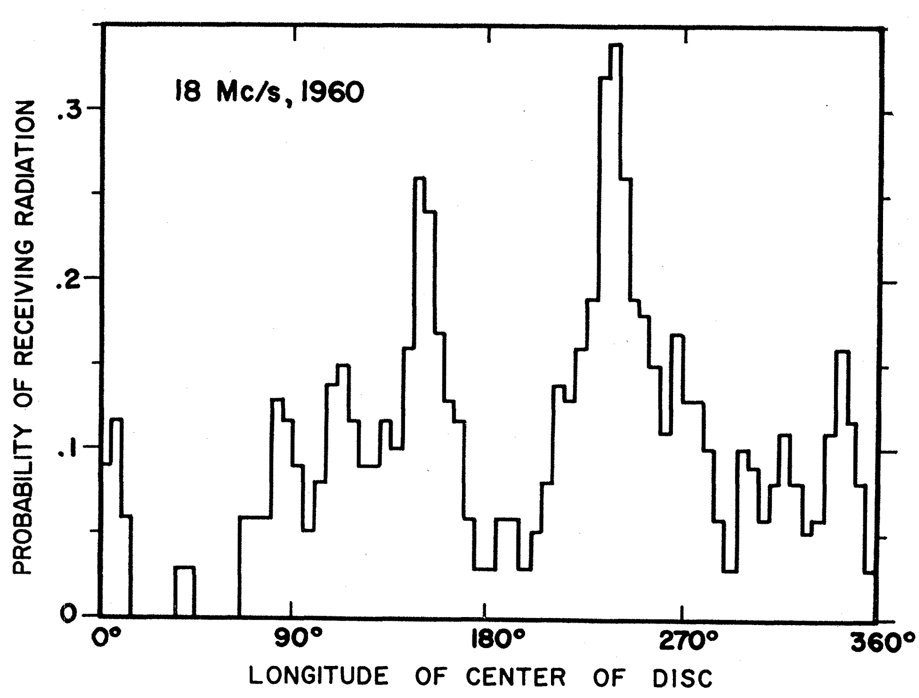

Fig. 2. A histogram showing how the probability of receiving radiation from Jupiter depends on the longitude of the center of the visible disc. For convenience in analysis, the planet has been divided into 5-degree zones of longitude. The longitude values shown here belong to System III, a new system which has been defined as rotating at the same rate as the radio sources (*3*).

proven to be different. Figure 4 shows the drift in System II coordinates of the radio sources, the Red Spot, and the three white spots during the past decade. It is evident that the periods are all quite different, and that the coincidences which have been observed from time to time have been fortuitous and temporary.

Details of the Radio Outbursts

A Jovian radio outburst may last only a few seconds, or it may continue for hours. Figure 5 shows a typical low-speed recording of a "noise storm," as the longer events have been called. High-speed recordings made during such outbursts (Fig. 6) reveal that each of the peaks in Fig. 5 is in general a complex burst consisting of a number of individual pulses. These elementary pulses commonly range from about 0.2 second to 2 seconds in duration, while the bursts themselves may last only a few seconds or as much as a minute. When a noise storm is heard in a loudspeaker it produces a distinctive rushing sound which one of my students aptly likened to waves breaking on a beach. To anticipate a question which is always asked, there is no evidence whatever to suggest that the signals are not of natural origin.

Because of the present southerly declination of Jupiter, we decided in 1959 to establish a field station at Maipú, Chile, where the planet could be observed close to the zenith, away from the concentration of terrestrial interference near the horizon (*6*). When we compared high-speed recordings taken at Maipú with those made simultaneously in Florida, some 4400 miles away, we found that the detailed correlation between the records was generally quite poor. Often when there was a strong signal in Florida there was no signal at all in Chile, while 15 or 20 seconds later the situation would be reversed (this effect may be seen clearly in Fig. 6). It appears that much of the "burstiness" of the Jupiter radiation—that is, the tendency of the signal to appear as short trains of pulses—is actually due to fading or scintillation in the terrestrial ionosphere (*15*). This conclusion is strengthened by the fact that such scintillations, with a similar fading period, have been observed for the radio stars. I am currently making a statistical comparison of the signals received at the two stations to determine to what extent the shapes of the elementary pulses themselves may be influenced by the ionosphere.

Measurements of the polarization of the Jupiter radiation—that is to say, of

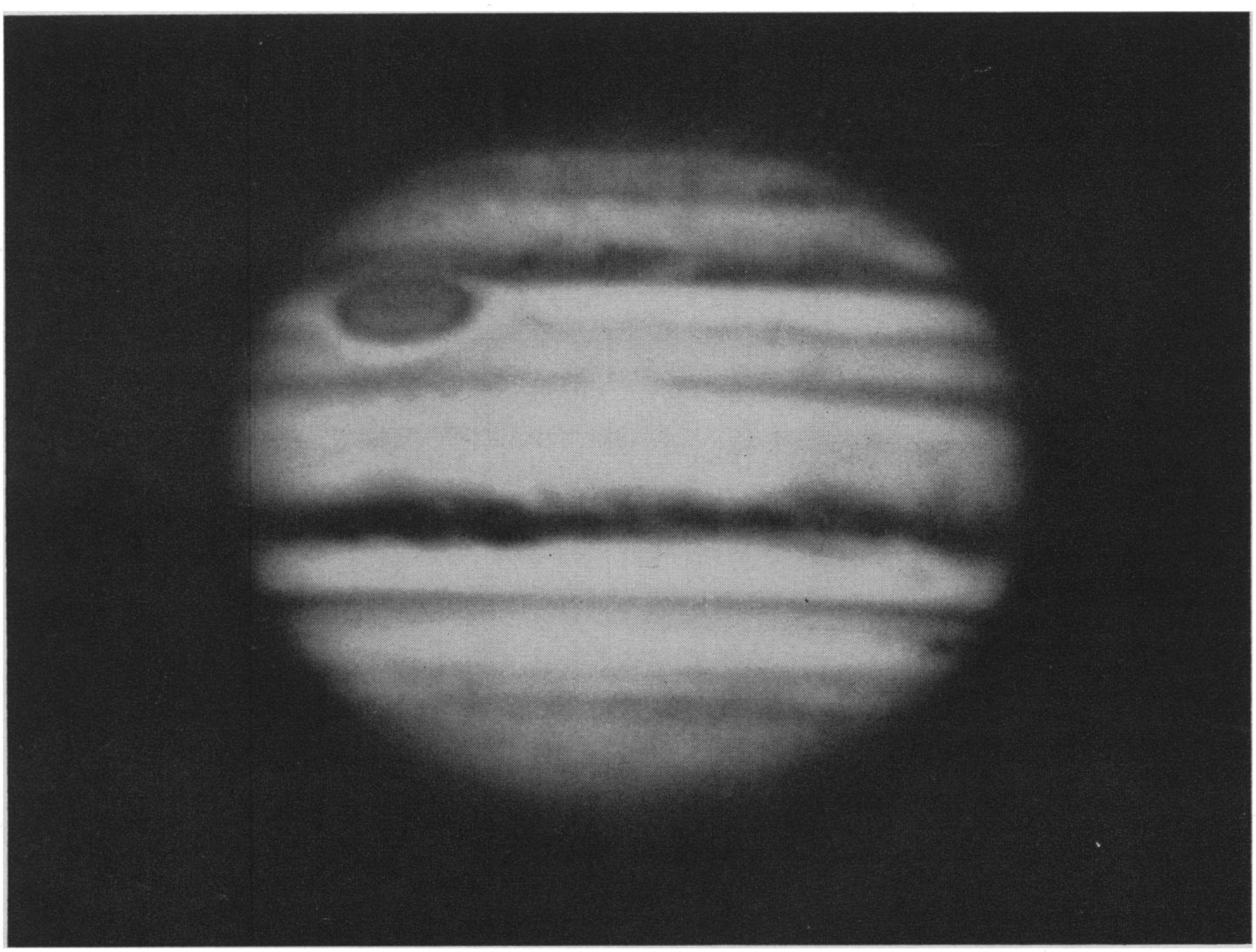

Fig. 3. A photograph of Jupiter taken with the 200-inch telescope of the Mount Palomar Observatory. Although its diameter is 11 times that of the earth, Jupiter turns on its axis in less than 10 hours. This rapid spinning causes the dense cloud cover to stream in belts parallel to the planet's equator, with clouds at the equator rotating faster than those in higher latitudes. Near the upper left edge of the disc may be seen the Great Red Spot, the longest-observed feature on the constantly changing face of the planet. [Courtesy Mount Wilson and Palomar Observatories]

the detailed manner in which the electromagnetic waves are vibrating—have been made by our group (*4, 5*), by Franklin and Burke (*9*), and by Gardner and Shain (*10*). All of the measurements have indicated that the great majority of the signals are circularly or elliptically polarized in the right-hand sense. Our results also show that there is a large pulse-to-pulse variation in the axial ratio of the polarization ellipse, although none of the observers has yet used equipment capable of determining the orientation of the ellipse.

Now, such polarization is quite likely to arise as a result of radiation passing through a magneto-ionic medium—that is, a combination of an ionosphere and a magnetic field. My associate T. D. Carr assumed a model in which (i) there was a Jovian ionosphere of the density suggested by the cone of escape of the radiation (although, as we have seen, there are difficulties with this interpretation); (ii) the radio sources were located near the latitude of greatest optical activity, that of the Red Spot; and (iii) the magnetic poles of Jupiter coincided with its axis of rotation. Using this model, Carr found that the observed polarization could be produced by a Jovian magnetic field of 7 gauss, a value about ten times that of the stronger regions of the earth's field (*4*). Although this value is admittedly only a crude estimate, it indicates that polarization measurements may ultimately reveal the latitudes of the radio sources and the presence or absence of a Jovian ionosphere, as well as providing a means of determining the strength of the magnetic field of the planet (*16*).

In 1960 we obtained simultaneous polarization records at the stations in Florida and Chile. Although the best records were marred somewhat by a partial malfunction of the Florida equipment, the data indicated that the same polarization sense was observed in both magnetic hemispheres of the earth. If this finding is verified in experiments now in progress, the terrestrial ionosphere and magnetic field will be eliminated as a possible source of the observed polarization effects.

A matter of obvious importance is the spectral bandwidth of the elementary pulses. Observations made simultaneously on channels differing in frequency by several megacycles per second seldom show much correlation between individual pulses, and it is clear that this places an upper limit on the bandwidth (*4, 9*). For several years we have been conducting experiments with two receivers connected to the same antenna. During noise storms the frequency separation of the receivers is systematically varied, while the receiver outputs are recorded on a two-channel high-speed pen recorder. Although the results are quite variable, the detailed correlation between the channels generally becomes poor when the receiver frequencies differ by a few tenths of a megacycle per second.

In 1960 we put into operation a swept-frequency receiver which continuously displays any 4-Mcy/sec segment of the spectrum on a cathode ray screen, while a motion picture camera photographs the screen several times each second. Although this equipment initially was able to record only the strongest bursts, it confirmed the belief that many of the elementary pulses had half-amplitude bandwidths of the order of several tenths of a megacycle per second, and it gave graphic pictures of the build-up and decay of the pulses (Fig. 7). The pulses often appeared to be bifurcated, and occasionally three or even more peaks at different frequencies were evident. The sensitivity of the equipment has now been increased, so that pulses of only moderate intensity are being recorded. Many of these show broader spectra, with half-widths around 1 Mcy/sec.

Noise storms commonly drift up or down the spectrum with the passage of time (*5*). Sometimes a storm will appear first on the highest-frequency channel and then show up at successively lower frequencies; or the drift may be in the opposite direction. Our 1960 data indicate that drifts toward lower frequencies were the more common. The rate of drift is highly variable, but values of a few megacycles per second per minute are often observed.

Microwave Radiation

A broad spectrum of so-called "thermal radiation" is emitted by every object which has a temperature above absolute zero. For bodies at the temperatures of typical planetary surfaces, this radiation peaks in the infrared and falls off rapidly at longer wavelengths. In the radio part of the spectrum the energy declines as the square of the wavelength, so that the best opportunity for detecting thermal radio emission from a planet lies in the microwave region. Even here, the largest antennas and most sensitive receivers must be employed. By making quantitative measurements of thermal radiation it is

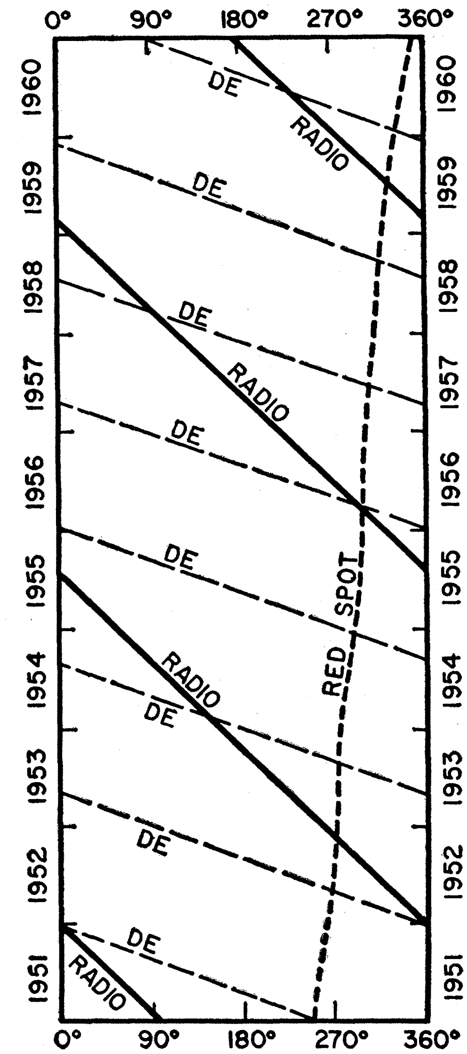

Fig. 4. A plot showing how both the radio sources and the few long-enduring optical features have drifted with respect to System II longitude coordinates during the past decade. To reduce confusion, only the position of the principal radio source is given, and the three white spots *FA*, *BC*, and *DE* are represented by the drift line of *DE* alone. The relatively slow drift of the Red Spot indicates that its period nearly matches that of System II, while the "waviness" in the drift line is due to irregularities in the Spot's motion. Although the white spots are near the latitude of the Red Spot, they rotate much more rapidly, gaining on the Red Spot by a complete lap in a little over a year. Notice that while the radio-source rotation period is only 11 seconds shorter than the rotation period of System II, the radio sources have gained nearly three laps on System II during the time they have been under observation. It is evident that the various drift lines periodically cross each other, producing temporary conjunctions of the radio sources and the visual markings.

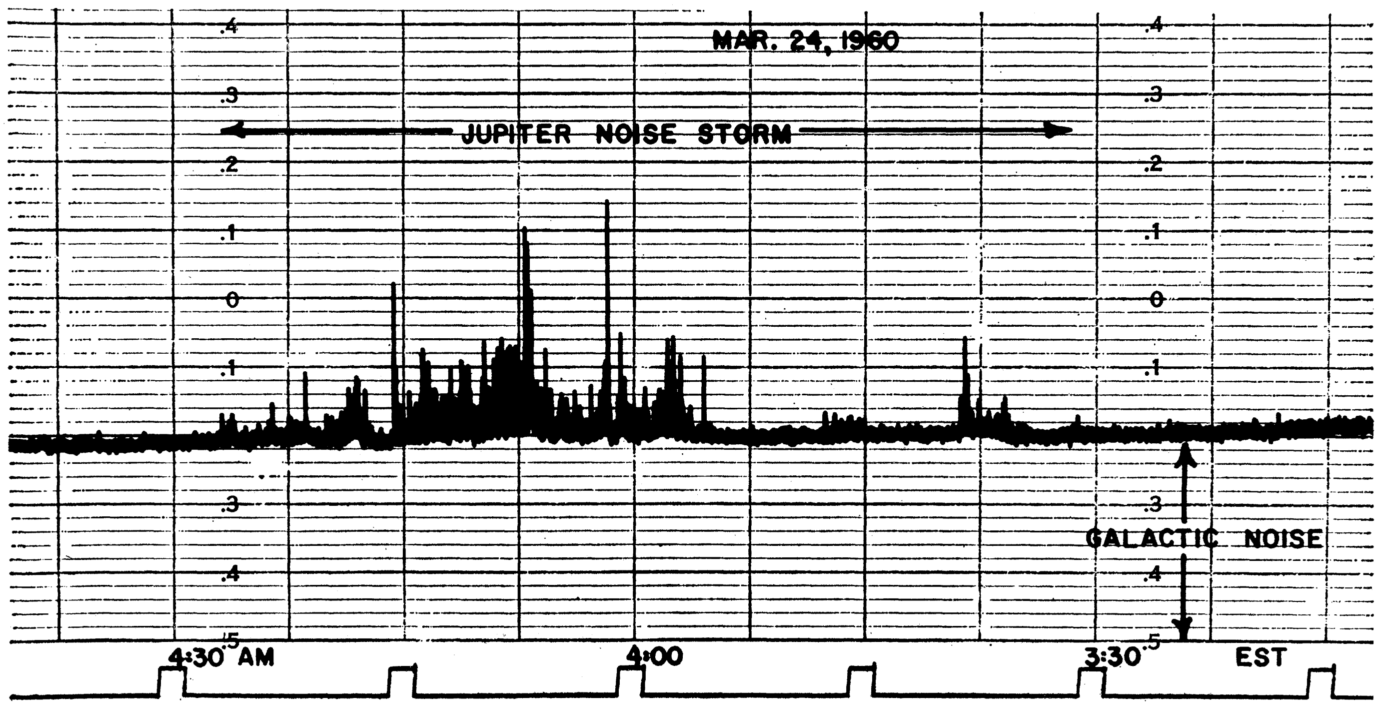

Fig. 5. A low-speed recording of a Jovian noise storm, made at the University of Florida at a frequency of 18 Mcy/sec. This storm, which lasted about an hour, was of moderate intensity and duration. The planetary bursts are always superimposed on a steady background signal emitted by our Galaxy (the Milky Way).

possible to compute the temperature of the source. Such measurements have long been made in the infrared by optical astronomers, and temperatures have been derived for the sun, the moon, and most of the planets. Early in the history of radio astronomy, radio temperatures were determined for the sun, and somewhat later, for the moon.

Thermal radio emission from a planet was first measured by Mayer, McCullough, and Sloanaker, in May of 1956. Using the 50-foot parabolic antenna of the Naval Research Laboratory at a wavelength of 3.15 centimeters, they obtained signals of sufficient strength from both Venus and Jupiter to permit estimation of the temperatures of those bodies (*17*). The value for Jupiter turned out to be 140°K, with an uncertainty of about 56°—a value quite compatible with the long-accepted value of 130°K, which had been derived from the infrared data. During the next 2 years the radio measurement was repeated by several groups, all of whom worked at wavelengths near 3 centimeters. None of the temperatures obtained seemed to differ very significantly from the original value of Mayer *et al.*, although it began to appear that the radio temperatures were always slightly higher than the values derived from optical data (*17, 18*).

The first real surprise was provided by McClain and Sloanaker, who made 60 measurements at a wavelength of 10.3 centimeters during the summer of 1958, using the Naval Research Laboratory's new 84-foot parabolic radio telescope (*19*). The individual temperature

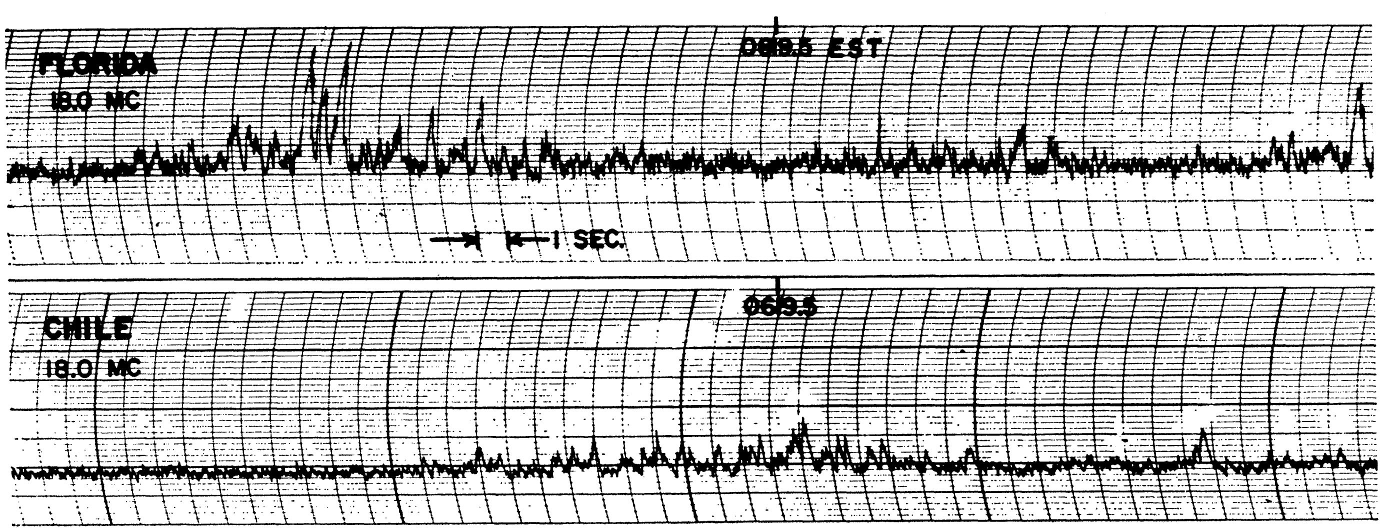

Fig. 6. High-speed recordings made simultaneously in Florida and in Chile, showing out-of-phase fading or scintillation. These high-speed recordings also resolve the elementary pulses of which the radiation is composed.

values ranged from 390° to 860°K, with a mean of 580°K. While there was some suggestion of correlation between the measured temperatures and the rotation of the planet, the experimental difficulties were such that the fluctuations could well have been due merely to statistical scatter of the data. In any event, this totally unexpected increase in the "temperature" of the planet with wavelength gave birth to immediate suspicion that a large fraction of the observed radiation might not, in fact, be thermal but might have some more complex origin, and other observers were stimulated to make measurements at still longer wavelengths.

During 1959, Roberts and Stanley found, in measurements at 31-centimeter wavelength (*20*), that the planet's "temperature" rose to 5500°K, while Drake and Hvatum made observations at 22 and 68 centimeters and found "temperatures" of 3000° and 70,000°K, respectively (*21*). The 22-centimeter data seemed to show statistically significant fluctuations, which were not, however, correlated with Jupiter's rotational period.

Figure 8 shows the dramatic way in which the computed "temperature" of Jupiter increases with wavelength if one interprets the microwave energy as being entirely of thermal origin. Of course, by 1959 it was quite obvious that most of the radiation at wavelengths above 3 centimeters must be due to some unknown phenomenon, and one more mystery was presented to the students of the giant planet.

Very recently Sloanaker and Boland reported that in late 1959 the temperature of Jupiter, in measurements at 10-centimeter wavelength, was 315°K, or about half the 1958 value. It is possible, however, that the difference was due to polarization effects resulting from the change which had occurred in the orientation of the planet with respect to the antenna (*22*).

Possible Mechanisms

There has been no dearth of speculation regarding the actual mechanism by which Jupiter emits its peculiar radio spectrum. Almost concurrently with the discovery of the decameter-wavelength radiation in 1955 there were suggestions that the outbursts might be ordinary "static" due to lightning-like discharges in the Jovian atmosphere (*8, 23*). A. J. Higgs, in fact, had suggested in 1951 the desirability of searching for such noise from Venus (*24*).

It shortly appeared that there were serious difficulties with the "lightning" theory. The narrow bandwidth and relatively long duration of the Jovian pulses were quite unlike terrestrial static. Furthermore, calculations indicated that the peak radio-frequency energy emitted by Jupiter amounted to about 10 kilowatts per cycle per second of bandwidth, an amount exceeding by several orders of magnitude the radiation due to terrestrial lightning strokes (*25*). As early as 1955, F. G. Smith discounted the lightning hypothesis and proposed that the energy for the radio outbursts might be supplied by the differential rotation of the planet—that is, by the slippage of the various atmospheric belts at different latitudes with

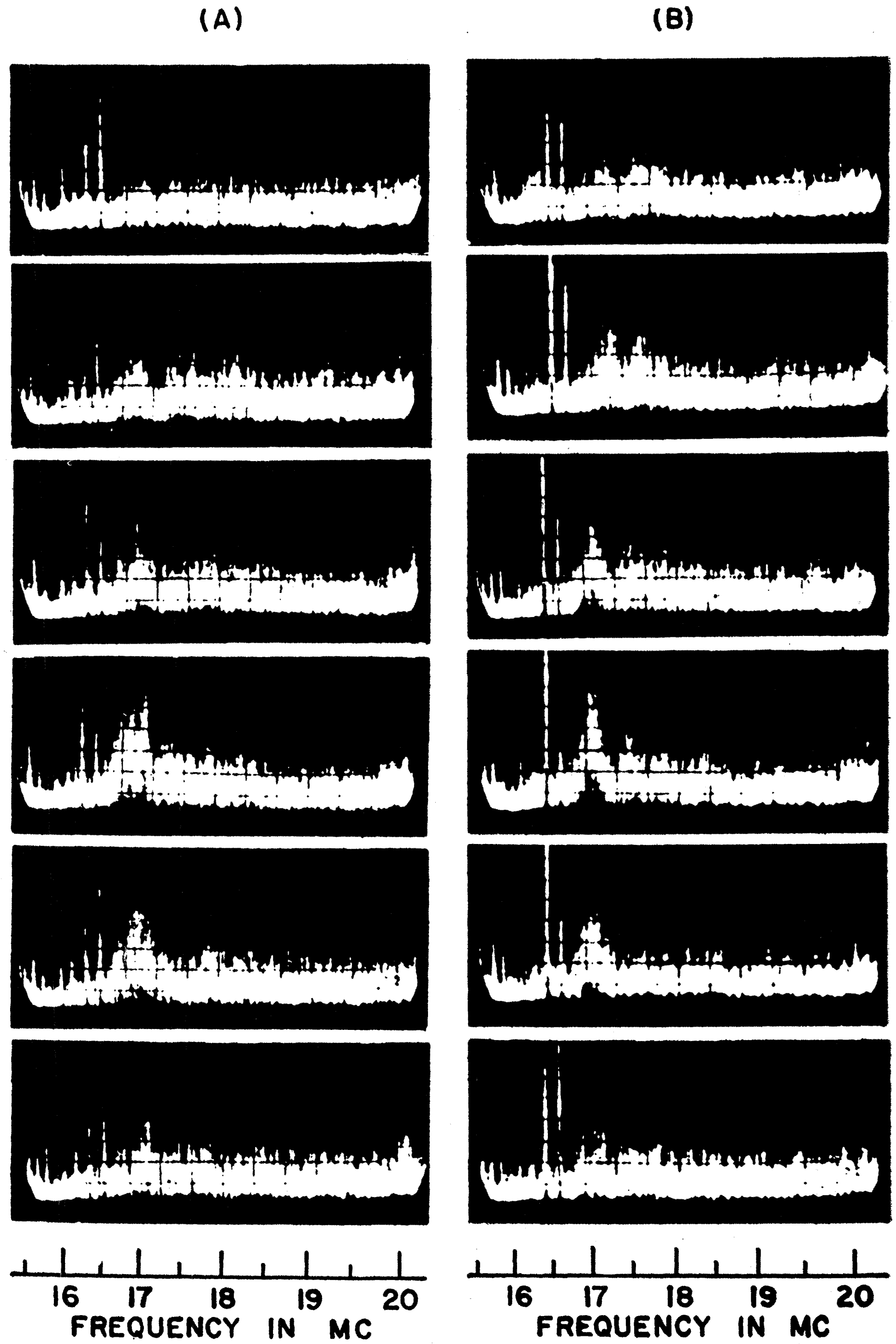

Fig. 7. Dynamic spectra of two Jupiter noise pulses near 17 Mcy/sec. Pulse *B* occurred about 6 seconds after pulse *A*. Time increases downward in each column at a rate of ½ second per frame, and the frequency scale is shown at the bottom. The narrow vertical lines at the left of the pulses are signals from radio stations. Note the splitting of pulse *B* in the first four frames.

respect to each other and with respect to the surface of the planet (*26*). In 1960 Field revived this idea, reasoning that electrical discharges could result from voltages induced by Jupiter's magnetic field slipping through its atmosphere (*27*).

In 1958 Zhelezniakov suggested that the decameter radiation is due to plasma oscillations in a Jovian ionosphere (*28*). A plasma is, of course, a highly ionized medium, and it has been demonstrated that if such a medium can be set into oscillation under favorable conditions it will emit radio waves. An attractive aspect of this theory was that such oscillations are generally believed to be responsible for similar outbursts from the sun. However, Zhelezniakov based much of his numerical calculation on the erroneous assumption that most of the Jovian radiation consists of pulses of millisecond duration, and he apparently felt that his theory could not account for the longer pulses of which the radiation appears to be composed. Gardner and Shain (*10*) and Gallet (*13*) made qualitative suggestions in 1958 that plasma oscillations might be excited by shock waves ascending from volcanic explosions on the surface of Jupiter.

Early in 1958 Kraus called attention to two occasions, in 1956 and 1957, when large solar flares were followed after an interval of several days by intense Jovian outbursts, and he proposed that the planetary noise might have been triggered by solar particles (*25*). It is well established that such solar explosions shoot out streams of charged particles, which reach the earth a day or two later and create such phenomena as the aurora borealis and various magnetic disturbances. The following year Eugene Epstein of Harvard suggested to us that if Kraus' hypothesis were correct, then when Jupiter is near opposition (that is, when the earth is between Jupiter and the sun), periods of geomagnetic activity should precede Jovian radio outbursts, since the solar particles would first strike the earth before reaching Jupiter. We were unable to look for this phenomenon in 1959, because opposition occurred during the summer, when thunderstorm activity made radio observations impossible much of the time in Florida.

By 1960 our Chilean station was in operation, and we were able to obtain radio data throughout the entire period around opposition. When these observations were compared with the geomagnetic data there was evidence that magnetic storms on the earth were indeed followed after an interval of some 5 to 12 days by Jovian radio outbursts (*29*). Warwick was making radio observations of both the sun and Jupiter in 1960, with a swept-frequency receiver, and he found an apparent correlation between Jovian noise storms and increases in the decameter radiation from the sun, with the solar activity preceding the noise storms by 1 or 2 days (*30*). The solar radio emission, like the flares, was interpreted as signaling the ejection of charged particles from the sun. In Warwick's correlation, based on an entirely different phenomenon from ours, the shorter delay time would seem to imply a much higher particle velocity, so that we have here an as yet unresolved discrepancy.

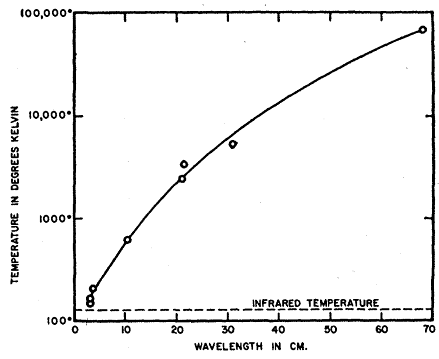

Fig. 8. A plot of the improbable way in which the "temperature" of Jupiter increases with wavelength, if the observed microwave energy is interpreted as being entirely of thermal origin. The points are mean values reported by various observers. Individual measurements fluctuate widely about these means, and in most cases it is not yet clear whether the variations are real or are merely due to the uncertainties of these very difficult observations.

If the decameter radiation from Jupiter is actually the result of bombardment of the planet by solar particles, it is not unreasonable to suppose that this bombardment might produce auroral activity, as it does here on earth. Unfortunately, we see only the daylight hemisphere of Jupiter, so that detection of such auroras poses a difficult optical problem. In 1960 we made photoelectric observations of the planet during several radio noise storms but failed to discover any significant fluctuations in its light (*5*). However, the experiment might well be repeated with more sensitive optical equipment than was then available.

Carr suggested in 1958 that the observed elliptical polarization of the low-frequency waves might be explained if the radiation were emitted directly by solar particles spiraling in the Jovian magnetic field (*31*). This concept has been developed extensively in various attempts to explain the anomalous microwave energy. Drake and Hvatum proposed that Jupiter may be surrounded by vast shells of trapped solar particles, analogous to the now-famous Van Allen belts of the earth (*21*), while Field (*27*, *32*) and Roberts and Stanley (*20*) have derived quantitative theories of such belts. According to these theories, the microwaves are either "cyclotron" or "synchrotron" radiation from electrons trapped in the planet's magnetic field.

It is well known that charged particles moving across a magnetic field are forced into circular orbits. This controlled motion, in fact, forms the basis of operation of nuclear accelerators such as the cyclotron. If the particles also have a component of velocity along the magnetic field, the circular orbits become helices centered on the lines of the field. Electrons in such orbits complete $2.8H$ million revolutions per second, where H is the magnetic field strength in gauss, and they consequently emit radio waves of the same frequency, which is known as the "cyclotron" frequency. According to the cyclotron picture of Jupiter's radiation, the observed wide band of microwave frequencies results from electrons moving in a magnetic field which varies extensively as the particles spiral back and forth from pole to pole of the planet. It is immediately obvious that the field would have to rise to over 1200 gauss to produce the 3-centimeter waves. While such a field cannot be dismissed as impossible, it is disturbingly large (the earth's external field has a maximum value of only ⅔ gauss) and it would probably produce detectable optical effects, such as splitting of spectral lines; no such effects have been observed.

If the trapped electrons possess very high energies, in the range where their relativistic increase in mass is appreciable, they will emit not only at the fundamental cyclotron frequency but at numerous higher harmonics of this frequency as well. This phenomenon is called "synchrotron" radiation, after the nuclear machine in which the effect was first observed. A synchrotron model of the Jovian emission greatly reduces the required magnetic field (the fundamental frequency can now be almost as low as one pleases), but it poses the new problem of accounting for a density of relativistic electrons which is at present inexplicably high as compared with the density in the terrestrial Van Allen belts.

The recent discovery by Radhakrishnan and Roberts (*33*) that the microwave radiation is strongly plane-polarized parallel to Jupiter's equator is consistent with either the cyclotron or the synchrotron theory. By using two 90-foot parabolic antennas as a huge interferometer, these observers have also shown that the microwave energy apparently comes from a region having about three times the diameter of Jupiter itself, confirming the theory that there is some kind of belt or halo about the planet. Needless to say, this region may constitute a most formidable radiation hazard to approaching space vehicles.

Conclusion

One of the outstanding mysteries in the young science of radio astronomy is presented by the radio spectrum of Jupiter. Throughout most of the ordinary short-wave bands the sporadic radiation from the planet is stronger than that from any other celestial source except the sun. Recently Jupiter has been shown to emit microwave energy of such intensity that it cannot be due to simple heat radiation. Lying between these two regions of the radio spectrum is a wide gap in which no Jovian energy has been detected.

The decameter radiation is strongly correlated with the rotation of the planet, a finding that suggests the existence of localized sources. It is suspected that the microwave radiation also fluctuates, but no connection with Jupiter's rotation has yet been demonstrated. The outstanding problem at the present time is that of establishing the mechanism by which the radio energy is generated; at the moment it is not even clear whether the two observed frequency bands have a common origin. Recent observations of the polarization and angular extent of the microwave energy are consistent with theories attributing that radiation to cyclotron or synchrotron emission from electrons spiraling in a Jovian magnetic field, but these models imply either a disturbingly large field or an inexplicably high flux of energetic electrons.

It is evident that much more observational material is required, in order to establish the temporal characteristics of the microwave radiation, to study in greater detail the spectra and polarization of the decameter outbursts, and to investigate the suspected correlation with solar and geophysical phenomena. In the latter connection the noise storms may prove to be an important tool for studying the propagation of solar disturbances beyond the orbit of the earth. Moreover, the radio signals, besides shedding new light on the physical conditions of Jupiter and its environs, might conceivably be used to guide space probes toward the giant planet, making it a relatively easy target. On the other hand, the neighborhood of Jupiter will obviously be a very noisy one from the point of view of space communications.

In the 6 years which have elapsed since the discovery of the intense sporadic radiation from Jupiter, no other planet has been shown to be a source of such outbursts. For a while it was believed that Venus was a strong emitter of decameter radiation (*34*), and some weak sporadic activity from Saturn has been suspected (*4, 5, 35*), but at present Jupiter still appears to be unique as a radio source.

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