RADIOPHYSICS OF JUPITER

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1. Introduction

1.11. *Thermal Radio Emission from Jupiter*

The atmosphere of the planet Jupiter emits thermal, black-body radiation at all wavelengths. The emission is strongest in the frequency range determined by $h\nu \sim kT$, where T, the atmospheric temperature, is of the order of 100° to 200°K. $\nu_{\max}$ is about 3×10^{12} sec^{-1}, corresponding to 100 microns, or 0.1 mm wavelength. This wavelength lies in a difficult range to study, too long to be reached easily by optical techniques, and too short for radio. Towards millimetric wavelengths, radio emission has however been detected (Low, 1966) and is produced entirely through thermal mechanisms in the outer layers of the planet's atmosphere. This emission is of interest in clarifying the still considerable mysteries of the atmospheric structure, but lies outside the scope of this review.

1.12. *Non-thermal Decimetric Emission (DIM)*

At longer wavelengths, from perhaps 5 cm to at least 200 cm, Jupiter produces a nearly constant radio flux of about 7×10^{-26} watts $\cdot$ meter$^{-2} \cdot$ (cps)$^{-1}$. This emission led to the conclusion that Jupiter possesses a system of 'radiation' belts, a dipole-like magnetic field containing large numbers of relativistic electrons (DRAKE and HVATUM, 1959).

1.13. *Non-thermal Decametric Emission (DAM)*

At wavelengths longer than 7.5 m (apparently a strict lower bound), Jupiter emits sporadic emission of high intensity, the flux often exceeding 10^{-20} watts $\cdot$ meter$^{-2} \cdot$ (cps)$^{-1}$ in strong events.

1.21. *Historical Remarks concerning DAM*

Radio emission from Jupiter was first recognized at 22 Mc/s by BURKE and FRANKLIN (1955). Previously unidentified observations in Sydney, Australia extended the records to 1950, and established quickly (SHAIN, 1956) that in a statistical sense, the DAM emission probability varies with a period about the same as the rotation period of mid-latitude optical features of Jupiter. Still earlier DAM data must have been obtained by Jansky during the years in which he discovered cosmic radio waves. Apparently these valuable original records were destroyed 20 years later during the relocation of the laboratory in which he worked (Harlan J. Smith, private communication).

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Soon after recognition of DAM, several observers established the predominance in the emission of right-hand elliptical polarization (GARDNER and SHAIN, 1958; FRANKLIN and BURKE, 1958), and this in turn suggested the existence on Jupiter of a magnetic field greater than four gauss (BURKE and FRANKLIN, 1956).

1.22. *Historical Remarks concerning DIM*

SLOANAKER (1959) first detected Jupiter radio emission in the decimetric range. The early observations already indicated a 'brightness temperature' for the emission, regarded as coming from the planet's optical disk, of 600°K. This value is much greater than the previous values from bolometric studies of Jupiter's infrared radiation (MENZEL, COBLENTZ, and LAMPLAND, 1926). The unexpectedly high temperature was soon very much exceeded by the brightness temperatures inferred from studies at still longer wavelengths, culminating in DRAKE and HVATUM's (1959) 70000°K at 400 Mc/s and the suggestion of Van Allen belts around the planet. Detailed studies, especially of the polarization and spatial extent of this emission, fully confirmed the suggestion. Furthermore, it became apparent that the dipole source of Jupiter's magnetic field rotated with a period close to that of DAM, and that the magnetic dipole axis was tipped about 10° to Jupiter's rotation axis (RADHAKRISHNAN and ROBERTS, 1960; MORRIS and BERGE, 1962).

1.3. SUMMARY OF AVAILABLE REVIEWS

Recently there have appeared a number of general reviews of Jupiter's radio phenomenology. These collectively summarize the status of the field. In particular, note ROBERTS (1963), DOUGLAS (1964), FRANKLIN (1964), WARWICK (1964a, 1966). SMITH and CARR (1964), ELLIS (1965), and KRAUS (1966).

1.4. THE PRESENT REVIEW

My objective is to summarize the observational and theoretical developments regarding the non-thermal emission from Jupiter, since 1963. The emphasis will be on new data, and their phenomenological interpretation. Unfortunately, a more basic, deductive analysis of Jupiter radiophysics does not appear possible with the present state of our knowledge of the planet. The 'cut-off' date of the review is roughly October, 1966, although some more recent material available in preprint form has also been included.

2. Io Modulation

2.1. HISTORY OF THE DISCOVERY

Unquestionably, the most striking new result of the last few years is the discovery that the first Galilean satellite (named 'Io' after a Greek nymph Jupiter changed into a heifer) strongly modulates DAM, especially at frequencies above 30 Mc/s (BIGG, 1964; DUNCAN, 1965). Bigg motivated his research by his conviction that geophysical effects of our own moon included important atmospheric influences beyond familiar tidal phenomena. After an inconclusive search of rather limited Australian DAM data, Bigg visited Boulder, where we had just completed a manuscript catalogue of DAM observed here from 1960 through 1963 (Warwick and Kreiss, 1964). In lending Bigg the new catalogue, we expected that our data would show no satellite effects whatsoever.

2.2. The relation at high decametric frequencies

Figure 1 (Dulk, 1965a) exhibits the actual relation, essentially as discovered by Bigg. The Boulder data were obtained from a radio spectrograph, which detects emission up to a frequency of 41 Mc/s. This frequency, higher by about 10 Mc/s than prior studies of DAM, is where the emission responds most sensitively to Io. At least a dozen radio astronomers had earlier studied synoptic DAM data without discovering the Io control.

I am one of them and, in their defense, would like to note that there are many systematic modulation effects in the synoptic data. This is true because the earth rotates and there is a short season for observing DAM. The beat period between

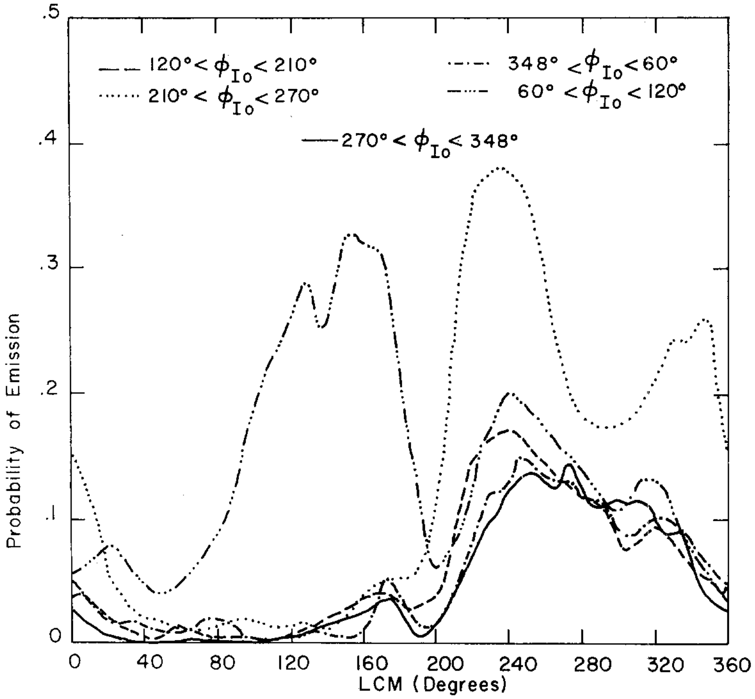

Fig. 1. The relation between the rotational profile of Jupiter's decametric emission, and the position of Io, the innermost Galilean satellite. Along the horizontal axis is plotted the radio longitude of the central meridian (LCM). ϕ_{Io} is the longitude of Io, measured from geocentric superior conjunction. ϕ_{Io} increases in the counterclockwise sense if you view Io's orbit from the north (after Dulk, 1965a). Note that 'early-source' emission, for which LCM lies from 80 to 200°, occurs overwhelming for ϕ_{Io} in the range 60° to 120°. Main-source emission, for which LCM is 200° to 280°, occurs for *all* longitudes of Io, although Io enhances this source also when ϕ_{Io} is in the range 210° to 270°. This figure contains data from all frequencies observed with the Boulder spectrograph, 7.6 to 41 Mc/s.

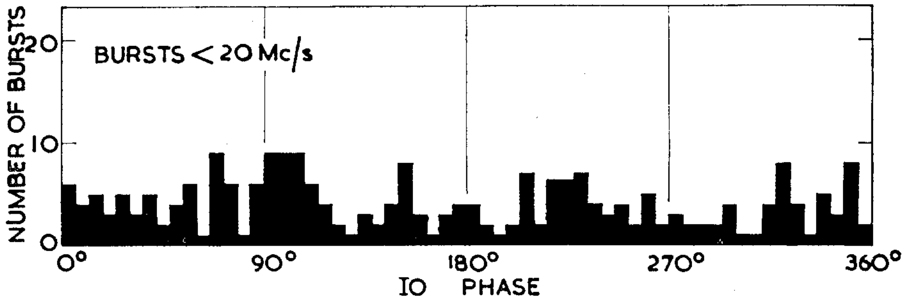

Fig. 2. The relation between the position of Io and Jupiter's decametric emission, for emission not extending above 20 Mc/s (after DUNCAN, 1966). The very prominent control of the all-frequency data by Io (Figure 1) has faded into relatively minor bumps at $\phi_{\mathrm{Io}} = 90°$ and 230°.

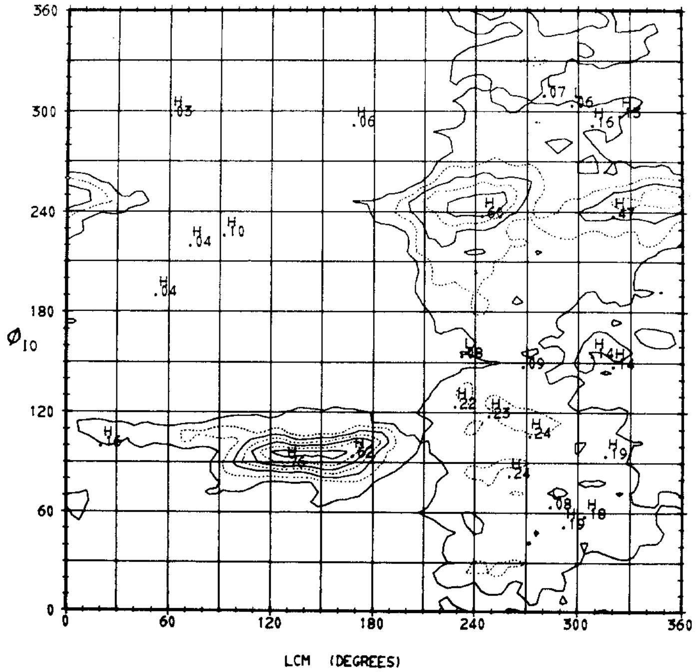

Fig. 3. The relation of DAM (all frequencies) to Io's longitude (ϕ_{Io}) and the radio longitude of the central meridian (LCM) (after DULK, 1965a). Fractional probability of emission is labeled for various points on the figure (H = high, L = low). Note the extremely strong peak of emission probability in the early source, between LCM 90° to 180° at $\phi_{\mathrm{Io}} = 94°$. The main source, between LCM 210° and 270°, occurs at all Io longutides, with a strong local peak at $\phi_{\mathrm{Io}} = 245°$, and much weaker peaks near $\phi_{\mathrm{Io}} = 90°$. Note also that the probability contours lie parallel to the abscissa (compare with Figure 4).

Jupiter's rotation and one-third of the earth's rotation is close to Io's synodic period of 42 hours 29 minutes. That is

$$\frac{3}{24\text{ hours}} - \frac{1}{9\text{ hours }55\text{ min.}} = \frac{1}{41\text{ hours }23\text{ min.}}.$$

However, Bigg showed that the Io modulation remained in phase for three years, long enough to rule out the difference of 1 hour 6 minutes. And, as Bigg noted, the result is of overwhelming statistical significance.

2.3. THE IO RELATION AT LOW DAM FREQUENCIES

Figure 2 (DUNCAN, 1966) exhibits a result for bursts entirely below 20 Mc/s, where the connection with Io fades strikingly. This result was independently found by LEBO *et al.* (1965b). The interpretation may well relate to the fact that Jupiter emission occurs a much larger percentage of the observing time at low than at high DAM frequencies. For example, Ellis suggested that Jupiter at 4.8 Mc/s was a continuous source, whose modulation with Jupiter's rotation could be seen best in the intensity of the emission as a function of longitude. Although ELLIS (1962) had only limited data, a result similar to this one is surely valid at 8.9 and 10 Mc/s (CLARK and DULK, 1966a, b). However, somewhat contradictory results were obtained by ZABRISKIE *et al.* (1965).

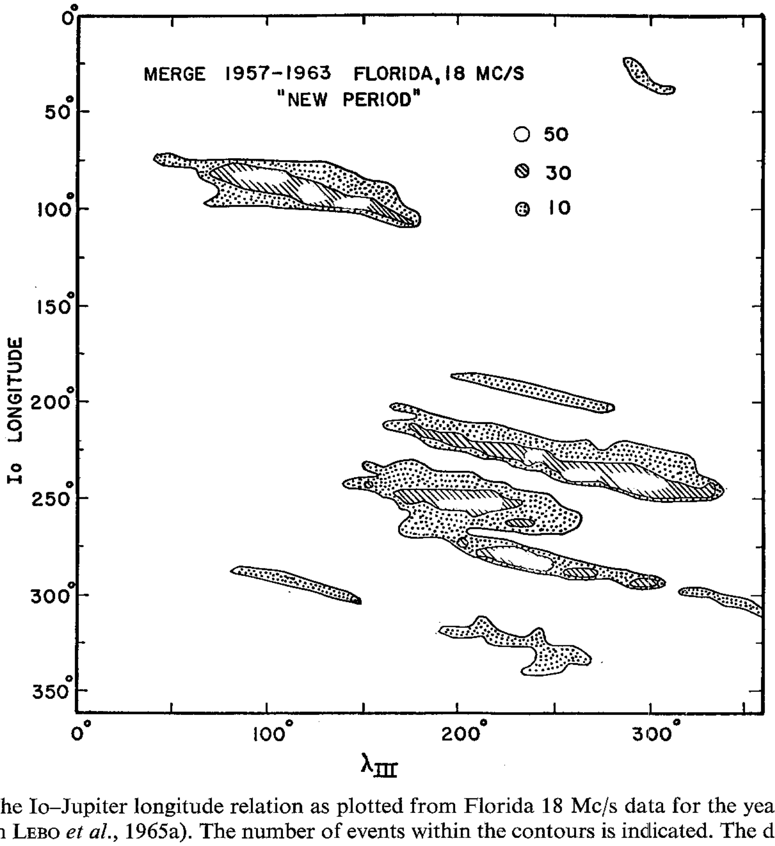

Fig. 4. The Io–Jupiter longitude relation as plotted from Florida 18 Mc/s data for the years 1957–1963 (from LEBO *et al.*, 1965a). The number of events within the contours is indicated. The difference between this figure and Figure 3 is primarily the presence here of *sloped contours* of emission occurrence. These contours are accurately inclined at the slope of a real-time point moving in the Io–λ_{III} coordinates. (The fact that Figure 3 was plotted on the basis of the System III (1957.0) period and Figure 4 was plotted on the basis of a period about one second longer does not explain the difference in appearance of the diagrams.)

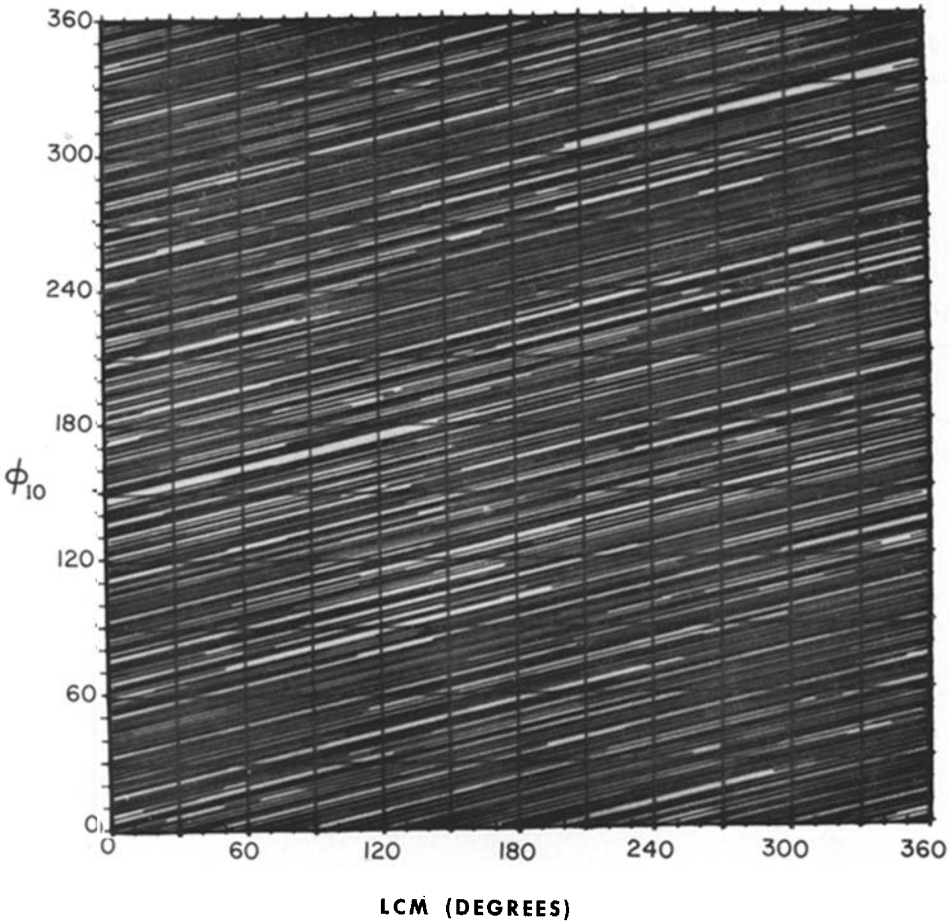

Fig. 5. A plot of all Jupiter observing periods for the Boulder spectrograph in the apparition of 1963 (Warwick and Dulk, 1966). Each observing period is shown as a sloped line. The totality of observing periods amounts to hours of observation, and the lines almost fill the diagram; however, conspicuous gaps are visible, extending over as much as 150° in λ_{III} (C.M.P.), and 4° in ϕ_{Io}. Overlaps are roughly indicated by relative darkness. Gaps or overlaps such as these can produce a sloped Io-System III relation such as in Figure 4. In order to avoid sloped contours, the data must be normalized and smoothed. Figure 3 has been prepared in this way. The conclusion is that the sloped contours of Figure 4 probably represent the statistical distribution of observing periods, rather than a physical phenomenon.

2.4. Joint relation with Jupiter rotation

Sufficient data can establish the two-parameter relation of the emission to the position of both Io and the planet. Figure 3 shows the relation according to Dulk (1965a), who used the Boulder spectrographic data. The plot is essentially identical to the one published by Bigg, although it is normalized, contains more recent data, and allows for some systematic corrections omitted by Bigg. Note that the 'early source' (in the longitude range 100° to 180°) shows a striking peak, with nearly unit probability for observable DAM when Io is near 93°. The 'main source', from 200° to 260°, has highest probability when Io is near 240°, but moderate probability exists at all Io longitudes.

2.5. DIFFERENCES IN THE RELATION OBSERVED AT VARIOUS STATIONS

Figure 4 shows the Io–Jupiter relation as suggested by LEBO *et al.* (1965a) on the basis of the Florida single frequency data at intermediate DAM frequencies. The general contours closely resemble the Boulder data. However, there is also a prominent striplike structure. These strips have a slope accurately described by the locus in real time of a point whose ordinate is the longitude of Io, and whose abscissa is the central meridian longitude of Jupiter. In the course of many months or years, these loci would fill the entire figure, since Jupiter's and Io's revolutions are incommensurable. The strip structure is therefore quite surprising if it is real. A similar strip structure is seen in Tasmanian data (MCCULLOCH and ELLIS, 1966).

However, WARWICK and DULK (1966) plotted DAM observations from Boulder in such a way that there is little or no smoothing of the data. Figure 5 shows that the observing periods define the same strip structure that appears on the Florida and Tasmanian emission probability contours. Since the observing periods are independent of the Io–Jupiter relation, we conclude that the strips are a spurious effect resulting from a more detailed plotting of the data than is warranted. A similar conclusion was reached by ALEXANDER (1966).

2.6. IO CONTROL OF EARLY-SOURCE DYNAMIC SPECTRA

One of the striking early results of spectral studies of DAM was that the central meridian longitude defines Jupiter's radio spectrum. I summarized this result (WARWICK, 1964a) in a montage of 26 early-source spectra obtained at Boulder in 1962 and 1963. The spectra were arranged into a sequence where each spectrum closely resembles its neighbors, but the initial and final spectra are quite different. Table I lists the spectra in the order they were published, and the central meridian longitude when the longitude of Io was 90°.

TABLE I

Dynamic Spectral Sequence

1.	16 VIII 62	84°	10.	30 IV 62	86°	18.	8 VI 62	145°
2.	21 VII 62	—*	11.	15 X 63	89°	19.	20 IX 63	150°
3.	15 VII 62	90°	12.	13 IX 63	112°	20.	22 X 63	139°
4.	4 II 63	91°	13.	24 IX 62	110°	21.	2 XI 62	145°
5.	6 IX 63	74°	14.	26 X 62	105°	22.	11 II 63	137°
6.	5 VIII 63	76°	15.	7 III 63	117°	23.	1 X 62	148°
7.	17 IX 62	72°	16.	3 V 63	152°	24.	21 IX 63	—*
8.	28 II 63	71°	17.	12 VIII 63	116°	25.	3 XII 62	—*
9.	1 IV 63	95°				26.	10 V 63	171°

* Io not close to 90°. These three events are among the poorest developed examples of early source spectra from the list of 26.

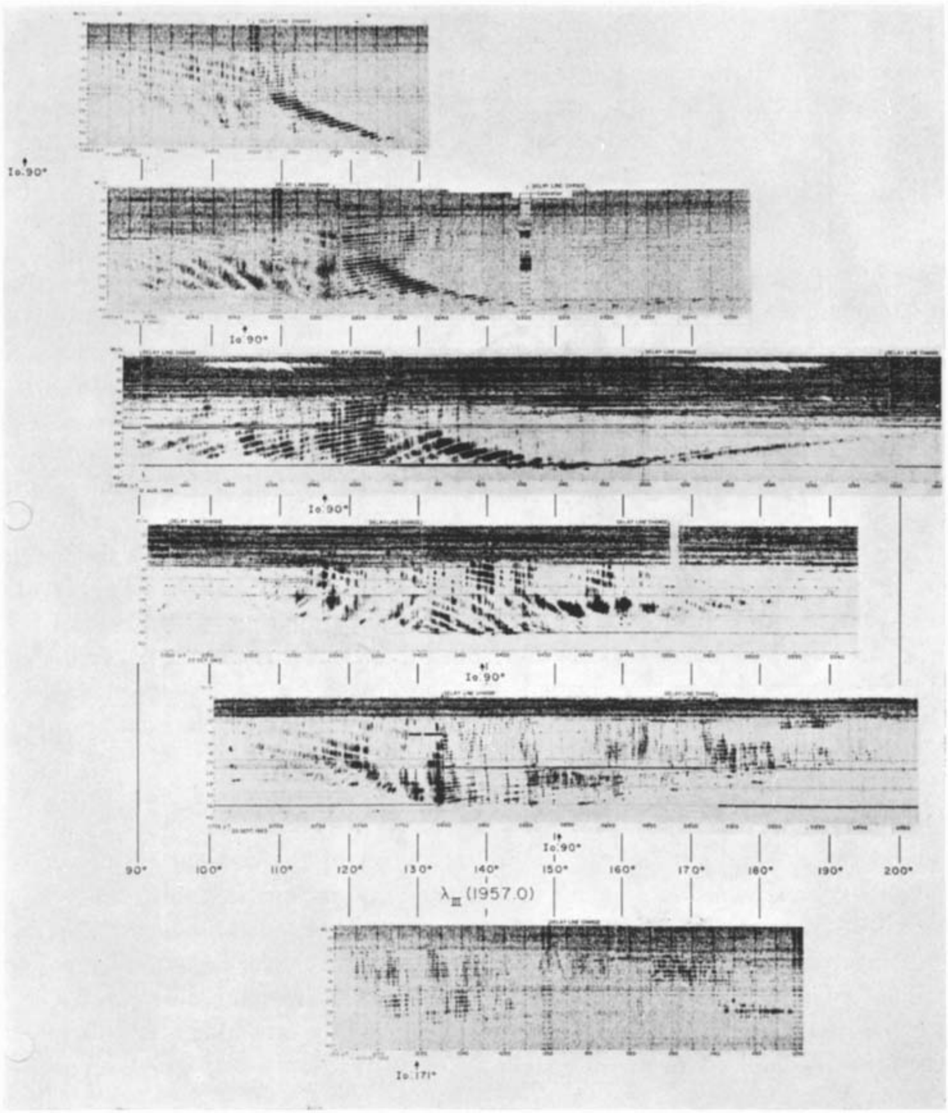

Fig. 6. The relation between dynamic spectral types in the early source, and the position of Io at the time of emission (from DULK, 1965a, b; 1966b). Each spectrum is mounted at its longitude according to System III (1957.0). The time when Io was at 90° longitude from superior geocentric conjunction is shown by an arrow below each spectrum. The 90° positions of Io span more than 60° in the longitude System III (see also Figure 7). The spectra vary systematically through the first five shown here. The sixth spectrum represents a quite distinct form, which occurred for a radically different position of Io. The first five spectra are, respectively, numbers 7, 14, 17, 20, and 19, in Table I. They were independently arranged in essentially the same order by WARWICK (1964a) as by Dulk. A typical difference in the Io = 90° position from spectrum to spectrum is 20° of System III longitude. This corresponds to a 5° change in Io's longitude. Note that the dynamic spectral features vary in longitude from spectrum to spectrum by a much smaller amount in System III than does the Io = 90° position. For example, the prominent stub of emission on the upper two spectra has the same λ_{III} range (to about 10°). The long persistent high frequency tail on the second and third spectra reaches its maximum frequency at almost exactly the same λ_{III}. Finally note that the highest frequency events occur when Io reaches 90° early in the event. The difference in maximum frequency amounts to about 5 Mc/s from the second record from the top, to the fifth record from the top.

There is a strong ordering of early-source dynamic spectral types according to the exact position of Io at the time of emission. Io lies very near 90° for nearly all these events. When Io has already reached 90° in the early part of the event, there occur spectra of one type (numbers 1 through 12); when Io comes to 90° late in the event, a different type of spectrum occurs (numbers 13 through 26). The ranking was done before the Io effect had been discovered. DULK (1965a, b; 1966) first recognized Io's control of the spectra, as shown in Figure 6. He also compared spectral observations of the main, third, and fourth source emissions by the same technique.

The possibility of effects on DAM from the other Galilean satellites, and also from Amalthea (Jupiter V) were considered by LEBO *et al.* (1965a). There is a strong dynamically-produced commensurability between the periods of the large satellites. Hence the strong Io effect introduces a short-term correlation between DAM and the position of each of the other satellites, but DUNCAN (1966) analysed the Boulder data and found no perceptible long-term effect of the other satellites. DULK (1965a) and WARWICK and DULK (1966) came to the same conclusion with the same data. A long period of data will be required to disentangle the Io effect and determine the effects of the other satellites (WARWICK, 1966). Since these satellites in all likelihood also move within Jupiter's magnetosphere, information on the magnitude of other satellite effects should eventually prove valuable in clarifying the source of the interactions.

2.7. INTERPRETATION OF THE IO EFFECT

2.71. *Geometrical Relations of Io and Jupiter at times of Emission*

Figure 7 (DULK, 1965b) shows the relative positions of Io and Jupiter during early- and main-source emission. The sensitive range in Io's orbit covers two 20° intervals, as shown. The sensitive range in the angular position of Jupiter's magnetic dipole is also shown for the early and main sources. The magnetic dipole position is found from polarization observations of DIM.

2.72. *Longitude Range of Control*

It may be significant that the end of the dipole in Jupiter's northern hemisphere inclines towards Io during the longitude range containing the majority of early- and main-source emission (at high enough frequencies). The nature of the high-frequency dynamic spectrum emitted towards the earth as Jupiter's dipole rotates past Io depends on Io's precise position in the sensitive longitude ranges. At very low DAM frequencies, emission appears at all longitudes. Above 15 Mc/s, there is a gap, a region of very low emission probability, between early and main sources. Regardless of Io's position, there is relatively high probability ($>10\%$) of emission at frequencies greater than 15 Mc/s every time the magnetic dipole longitude lies within the main source range indicated by 90° on the inner circle of Figure 7.

2.73. *Phenomenological Interpretation*

The satellite Io revolves outside DIM's observed limit of four to five radii from the

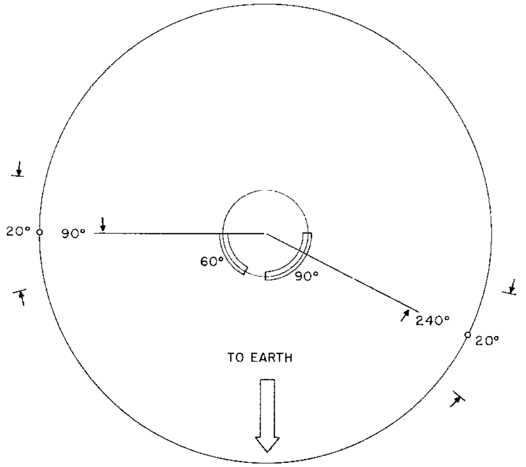

Fig. 7. The outer circle represents Io's orbit as seen from the north (after Dulk, 1965b). Io is shown at the two positions, 90° and 240° (measured from superior geocentric conjunction), where it strongly enhances high frequency decametric emission. Its control is nearly as strong in the 20°-range shown around these positions. The inner circle represents the longitude of the northern end of Jupiter's magnetic dipole. The dipole must lie within either of the two ranges labeled 60° (early source) or 90° (main source) for there to be decametric emission. The two sets of emission conditions, on Io and on the magnetic dipole, are necessary and sufficient. Whenever the northern end of Jupiter's magnetic dipole sweeps past Io, emission propagates simultaneously into two directions, the early and main sources. We can see this from the figure since the early source could as well be to the right of the 240° Io position, and the main source to the left of the 90° Io position. Such emission is of course not seen from the earth. However, its existence is a strong inference directly based on the observational data. There is an overlap of approximately 30° where emission propagates simultaneously into the early and main sources. This 30°-range of dipole position lies clockwise from the sub-Io position.

center of Jupiter. It moves in a nearly pure dipole field (see Section 11.4). There can be no significance to the Io longitudes of 90° and 240° as far as physical phenomena at the satellite itself are concerned. The disturbance created by Io must be continuously present at each point along Io's orbit around Jupiter. Given this conclusion (based on the symmetry of Io's orbit around Jupiter) we infer that the non-dipolar field configuration closer to Jupiter produces the observed Jupiter rotation effects on DAM. It should be emphasized that by dipolar, we mean a strictly centered dipole; non-dipolar implies any other configuration. (A non-centered dipole also would be 'non-dipolar', by this definition.)

High frequency DAM probably emanates from Jupiter every thirteen hours, but Io's position and the longitude of the magnetic dipole are usually such that the emission goes into directions other than the earth. The exact direction is an extremely sensitive function of the position of Io relative to the earth, a 10° change being sufficient to cause observable modifications in the character of the dynamic spectrum generated by Jupiter's rotation. The modifications primarily occur in the upper limit of the frequency emitted in DAM; the spectrum remains recognizably 'positive' drift for the early source and 'negative' drift for the main source, for all positions of Io within the sensitive range of Io longitudes.

Io controls high-frequency emission over a considerable range of longitudes of the magnetic dipole (see Figure 7). We believe this implies that Io's position controls the latitude of the source at Jupiter. Io's influence covers 80° of dipole longitude in the early source, whose spectrum develops in a continuous manner over the entire range. A slightly different position of Io produces nearly, but not exactly, the same steady continuous pattern of spectral development over just as great a longitude range. The difference in the patterns, it would seem, must therefore lie in the latitude of the excited region on Jupiter rather than in its longitude. The same wide range of longitude is covered in both cases. Furthermore, the same facts suggest strongly that the field at the surface of Jupiter is roughly axisymmetric.

The range in latitude that is involved might be inferred from the variation of the permanent dynamic spectrum from one position of the satellite to another. We consider that a 10° change of Io's position causes a 5 Mc/s change in the upper limit of the frequency over a wide range in longitude. There is an equivalent range in latitude. Assume that the field is a planet-centered dipole, and assume that the emitted frequency is the local gyro frequency. The change in latitude required for a decrease in field strength by 12.5% is given by

$$\Delta H/H = -\frac{1}{8} = +\frac{3}{2}\frac{\sin 2\,\theta}{(1+3\cos^2\theta)^{\frac{1}{2}}}\Delta\theta,$$

where $\Delta\theta$ (radians) is the change in co-latitude, θ. Assuming $\theta = 24.1°$, we find $\Delta\theta = 12.0°$. If the dipole is not planet-centered, then a smaller change in magnetic latitude might suffice. The noticeable change in the spectrum with such a small change in latitude implies that the emission is beamed into a 12° cone. This beaming is consistent with the 10° beaming determined from the permanent dynamic spectrum (WARWICK, 1963a).

We can similarly estimate the variation in L-shell occupied by Io needed to obtain the same 12° latitude change at Jupiter. Assume that the disturbance propagates along the dipole line of force through the satellite. Then the required change is from 6 Jupiter radii (the actual radius of Io's orbit) out to 17 Jupiter radii, impossibly large. We conclude that Jupiter's magnetic field near the planet cannot be represented by a planet-centered dipole.

The control by Io is so complete that we can assume there is emission into the ecliptic plane in both sources simultaneously when Io is positioned properly, regardless of whether the earth lies in the appropriate location to view the emission (DULK, 1965c). This feature of the Io control led DAVIS (1966) and DULK (1967) to suggest a model in which radiation is beamed primarily in the direction at right angles to the magnetic field near the surface of Jupiter. Io creates a 'hot spot' at the planetary foot of the line of force passing through the satellite; emission goes into a nearly equatorial cone around this line of force. The ecliptic plane intersects this cone at two longitudes, the early and the main sources.

WARWICK (1963a) suggested another model for the emission, before the Io control was discovered. The emission was generated along a line of force; only particles on the lines of force within a definite L-shell range 'activated' the emission at the surface of the planet. All longitudes were simultaneously active, but only a narrow range of latitudes. The points at which the magnetic field reflected from the surface of Jupiter towards the earth produced observable emission.

Just the mere fact of the Io control shows the vital importance of L-shell dependent interactions between Jupiter's magnetosphere and ionosphere. This was the starting point of Warwick's theory, which in that respect now seems to be confirmed.

But the new information is that the emission depends not only on the Jupiter magnetic field orientation (which was already a vital part of the early theory) but also on Io's position. We face two extreme possibilities: (1) the radiation created by Io's interaction must go into two directions simultaneously and a single small range of Jupiter longitudes is excited by Io (this is the essence of Dulk's and Davis' argument); or, (2) the radiation is beamed along the lines of force and a wide range of Jupiter longitudes is excited by Io. (In this way Io's control is introduced into Warwick's theory.)

In either case, the latitude of the excitation probably depends critically on Io's position. Whether a wide range or narrow range of longitudes is activated by Io, the narrow latitude range ensures that the character of the emission will depend critically on Io's position. Therefore, it is not necessary to assume a point-like region of excitation. In fact, as WARWICK (1964) discussed the matter, the implied equatorial beaming leads to difficulties in other respects. We conclude that a narrow latitude zone contains DAM-activating waves or particles; the same zone produces both main and early source emission. This zone is excited by Io only within a narrow range of Jupiter–Io orientations, and is variable in position within this narrow range. Whether we observe the emission depends on Jupiter's orientation with respect to the earth.

3. DIM Rotation, Brightness Distribution, and Polarization

3.1. MULTI-FREQUENCY OBSERVATIONS

The first interferometric data, by RADHAKRISHNAN and ROBERTS (1960), showed that the 960 Mc/s DIM came from extended regions surrounding Jupiter, and was strongly polarized (30%, E-vector equatorial). These results have been extended to 610 Mc/s by BARBER (1966) and to 1420 and 3000 Mc/s by BERGE (1965a, b; 1966). Lunar occultations of DIM, although somewhat inconclusive, indicate the same broadly distributed emission source as do interferometer measurements (ROBERTS and KOMESAROFF, 1965). Roberts and Komesaroff also obtained detailed polarization and intensity variations at 300, 408, 960, 1420, 2650, 3000, and 5000 Mc/s.

Sensitive observations of the exact relative position of DIM with respect to the planet are important; they may verify, qualify, or disprove the existence of the strongly asymmetric field inferred by me in my explanation of DAM. These measurements are at best difficult; they should establish the centroid to within a fraction of a planetary radius, within two or three seconds of arc. ROBERTS and EKERS (1966) made a direct pencil-beam comparison of DIM with the radio source CTA-21, which was only $\frac{1}{2}°$

away at the time. The differential measurement was carried out with remarkable internal consistency. Although the half-power beamwidth of the antenna was 450 seconds of arc, the data demonstrate that the centroid of DIM lay within two seconds of arc of the planet's optical centroid in right ascension, and within 10 seconds of arc in declination. Relative displacements of only one part in 225 could thus be detected. Since two sources were involved, the feat was even more remarkable, each source being measured to about one part in 300. Generally speaking, pencil-beam measurements are less precise, about $\frac{1}{20}$ of a beamwidth.

ROBERTS (1965) and ROBERTS and KOMESAROFF (1965) give a detailed summary of the Parkes (210-foot paraboloid) observations of the position angle variation of DIM's polarization as a function of frequency. To represent the asymmetry in the curves of position angle as a function of planet rotation, the second harmonic amplitude is about 20% of the fundamental at low frequencies, and is smaller at higher frequencies. Roberts and Komesaroff offered no interpretation of this observation beyond its indication of asymmetries in Jupiter's magnetic field. WARWICK (1964a) suggested that the planet shadows parts of the radiation belts (which are shifted strongly to the south in accordance with his theory of the decametric emission). However, theoretical arguments on the magnitude of this 'vignetting' suggest that it is not 20% but only about 6% of the total flux (ROBERTS and KOMESAROFF, 1965). Detailed calculations of synchrotron radiation from a dipole field are now available (ORTWEIN *et al.*, 1966), and the magnitude of the vignetting should be recalculated.

3.2. DISPLACED-DIPOLE MODEL OF JUPITER'S FIELD

There are some further DIM data bearing on the question of the dipole's location. ROBERTS (1965), ROBERTS and KOMESAROFF (1965), and BARBER (1966) find a north–south asymmetry in the intensity of DIM when it is plotted as a function of zenomagnetic latitude.* The intensity of the emission falls much more steeply in southern latitudes than in northern. The zenomagnetic latitude is defined by the measurements of the position angle of DIM's polarization. The Jupiter dipole is inclined at 10° to the rotation axis, rotates with the period of System III (1957.0), and lies in the subterrestrial longitude $\lambda_{\mathrm{III}}(\mathrm{CMP}) = 198°$. At that central meridian longitude, the northern end of Jupiter's dipole is inclined towards the earth.

In Figure 8, I have re-plotted Roberts' interesting figures on a different basis. Let northern zenomagnetic latitudes be positive and define a new zenomagnetic latitude $\phi' = \phi - 1.2°$. With this scheme, the intensity variation is identical in both positive and negative ranges of ϕ', and is given by $\cos^4\phi'$. The constant 1.2° is established to about 0.1° or 0.2° by the original data. Figure 8 shows that there is a cone of directions symmetrically arranged around zenomagnetic latitude $+1.2°$ for which DIM is most intense.

This result suggests that Jupiter's magnetic field configuration is axisymmetric, although other interpretations are possible. For instance, if different longitudes had

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* The term 'Joviomagnetic' appears in the literature instead of 'zenomagnetic'. I shall use the latter, which is consistent with prior usage (PEEK, 1958).

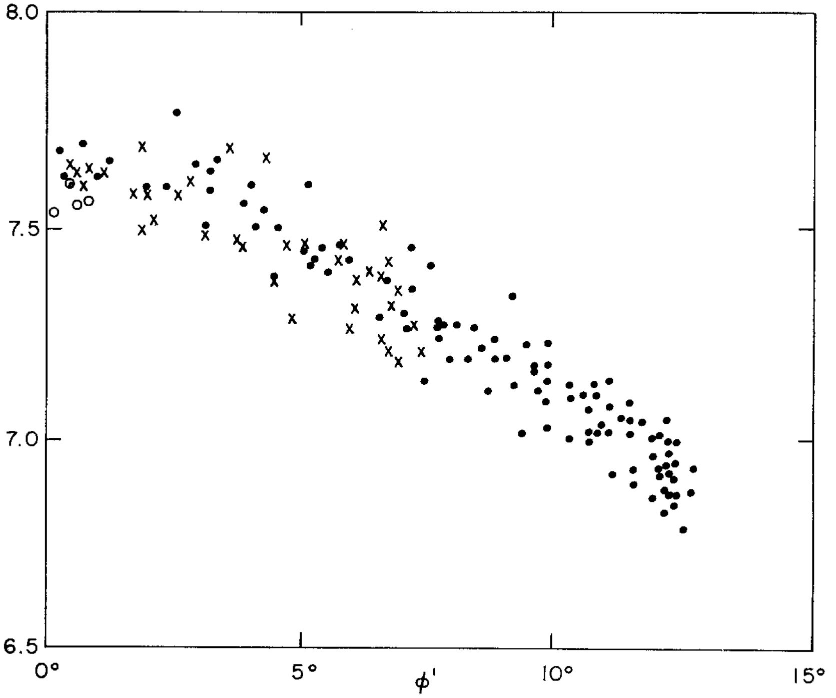

Fig. 8. (See Section 3.2 and 11.4 for a full discussion.) The relation between total intensity (in units of 10^{-26} w.m^{-2} · (cps)$^{-1}$) of 11.3 cm decimetric emission and $|\phi'| = |\phi - 1.^\circ 2|$. ϕ is the zenomagnetic latitude of the sub-earth point in a coordinate system rotating at the period of System III (1957.0) and having its polar direction inclined 10.°0 to Jupiter's rotation axis. The north rotation axis, north magnetic pole, and the direction of the earth are in the same plane when $\lambda_{\text{III}} = 198^\circ$. The data are from ROBERTS (1965), but are replotted on the basis of ϕ'. Solid points represent data from Jupiter's northern hemisphere and crosses represent data from Jupiter's southern hemisphere. The four open circles are northern hemisphere points for which $\phi \leqslant^{+} 1.^\circ 2$, or $\phi' \leqslant 0^\circ$. The intensity is closely proportional to $\cos^4\phi'$. In Roberts' original plot, northern latitudes follow such a $\cos^4\phi$ law, but southern latitudes follow the law $\cos^9\phi$. The agreement, in Figure 8, of both northern and southern latitudes with the law $\cos^4\phi'$, argues that the radiation is axisymmetric and is meridionally symmetric around north magnetic latitude $\phi = +1.^\circ 2$. We conclude that Jupiter possesses a weak, axisymmetric quadrupole magnetic field component (see Section 11.4).

different (non-axisymmetric) configurations, something like this could conceivable result. However, the data fit the axisymmetric hypothesis excellently, thus suggesting that Jupiter's field is mainly dipolar but has an axisymmetric quadrupolar component. As we shall see later (Section 11.4) this is consistent with a zenomagnetic surface field strong in the planet's southern hemisphere.

The result is *not* consistent with a pure dipole field. Vignetting of a displaced dipole radiation belt system cannot explain it. Although the shadowing model may explain why the radiation intensity is greater at southern latitudes than at northern latitudes, it does not explain the narrow secondary minimum found by Roberts.

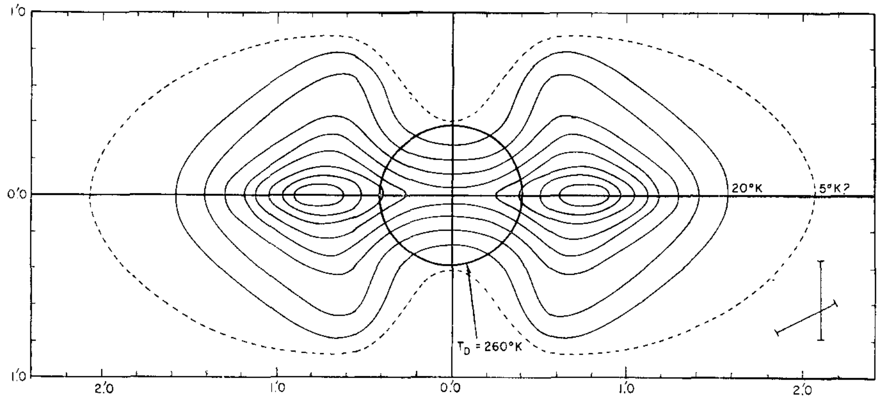

Fig. 9. The brightness distribution of DIM at 10.4 cm for $\lambda_{\rm III}$ (C.M.P) = 20° (after BERGE, 1966). The horizontal and vertical distance scales are in minutes of arc at the standard distance of 4.04 AU, corresponding to Jupiter's opposition. Note the high temperature of the disc inferred by Berge. This distribution was derived on the basis of many individual interferometric visibility curves. It is not necessarily a unique representation of the data, but is a plausible inference.

3.3. BRIGHTNESS DISTRIBUTION

Berge (1965a, b; 1966) proposed a multi-component model to represent the distribution of 10 cm radiation. This procedure is phenomenological, and is not intended to represent the full range of possible descriptions that could be given to the data. Therefore, a full instantaneously-recorded pencil-beam determination of DIM's pattern on the sky would be of great value.

Figure 9 shows Berge's suggested brightness contours of 10 cm radiation, which include an interesting new result on the high temperature (260°K) required to represent the thermal emission from the planetary atmosphere. In general, the contours agree with the earlier determinations.

3.4. DIRECTION OF JUPITER'S MAGNETIC FIELD AT TWO TO THREE RADII IN THE EQUATORIAL PLANE

In a separate report, BERGE (1965b) revises his earlier analysis of an apparent oscillation of the DIM centroid and concludes that there is a small (5%) component of circularly polarized radiation in DIM. His positional data are now consistent with the data observed by ROBERTS and EKERS (1966). In addition, the sense of the circular polarization permits a determination of the orientation of Jupiter's equatorial magnetic field in the radiation belts where DIM originates. The observed circular polarization is left-handed when zenomagnetic latitudes are positive. The polarization of waves emitted by electrons radiating along the lines of force is right-handed in the positive direction of the field, and left-handed in its negative direction. Berge therefore concluded that the positive end of the field vector lay pointed essentially southward in the belts. This corresponds to a dipole moment parallel to Jupiter's rotation axis (within 10°) rather than antiparallel. The latter is the case with the earth. Jupiter's field is opposite, in relation to Jupiter's rotation, to the case of the earth's field in relation to the earth's rotation. This result agrees with Warwick's (1963b) conclusion based on a theory of DAM.

3.5. SYNCHROTRON EFFECT IN JUPITER'S BELTS

The observed emission represents a volume integration over a wide range of magnetic field orientations and strength, and over a large range of electron energies and pitch angles. Definitive conclusions on any of these parameters are impossible in the circumstances. Barber and Gower (1965) give a more detailed discussion than the following.

The observed flatness of the DIM spectrum suggested to many observers that the electrons have a differential energy spectrum of the form $\mathrm{N}(E) \propto E^{-1}$, much flatter than the E^{-5} energy spectrum of the earth's belts. This conclusion does not seem to be particularly safe. Since the field may well range over as much as ten to one in strength, there will be very great overlapping in the frequency bands of the different energy ranges. It would be of great value if the DIM spectrum could be observed separately for each part of the source.

To estimate the field strengths, electron energies, and particle densities required for the observed emission, consider a typical peak frequency of 500 Mc/s and a bandwidth of 5000 Mc/s. A rough equation relating electron energy to this bandwidth is $5000\ \mathrm{Mc/s} = 10(E/E_0)^2 B_0$, where $E_0 = 550000$ eV and B_0 = field strength in gauss. The observed flux density from Jupiter is about 7×10^{-26} watts · meter^{-2}·(cps)$^{-1}$. If we assume that this emission comes from a solid angle the size of the planet (3×10^{-8} steradians) its intensity is $7 \times 10^{-26}/3 \times 10^{-8} = 2 \times 10^{-18}$ watts·meter^{-2}·(cps)$^{-1}$·sr^{-1}. In each square meter along the line of sight there are $10^4 N_e L$ electrons (N_e = electron density in numbers cm^{-3} and L = path length in cm). If these electrons move in flat spirals they radiate intensity $2 \times 10^{-18} = 10^{-24} N_e L(E/E_0)\, B_0$. We have added two unknowns, N_e and L, and only one equation. We take L to be a typical path through the radiation belts, say 4×10^{10} cm. Furthermore, if we assume the surface field strength of Jupiter is given by equating DAM to the gyro frequency, we can estimate the radiation belt field strength. A 10 gauss field extrapolated via the inverse cube law out to three Jupiter radii gives a field strength of 0.3 gauss. Then, $E = 20$ MeV, and $N_e = 4 \times 10^{-6}$ cm^{-3}. The flux of electrons, $N_e c = 10^5$ cm^{-2}·sec^{-1}. (In this estimate, E and N_e depend only weakly on B_0, as $B_0^{-\frac{1}{4}}$.)

These values compare quite closely to the ones derived by Barber and Gower (1965). In the earth's radiation belts, the flux of relativistic electrons with $E > 1.6$ MeV is about $J_0 \sim 10^6$ cm^{-2}·sec^{-1} (Frank *et al.*, 1963). In Jupiter's belts, a field as low as .01 gauss would be able to trap the electrons; lower fields probably could not contain the high electron energies (100 MeV) then required. These 20 MeV electrons can survive in a 0.3 gauss field for a century against radiative energy losses. In a field of one gauss, the required 10 MeV-DIM electrons survive for only about one year, probably not long enough. Without recourse to DAM estimates of field strength at all, the minimum relativistic electron flux appears to be about 10^5 cm^{-2}·sec^{-1}, close to the probable flux estimated in the preceding paragraph.

3.6. AN IO EFFECT ON DIM?

Several authors (BARBER, 1966; DICKEL, 1965) report no detectable Io effects on DIM's total intensity, but no results are available regarding the regions nearest Io. It is a curious paradox that DIM is generated near Io and shows no satellite effects, while DAM is generated remote from Io and is strongly influenced by it.

4. Rotation of DIM and DAM

4.1. HISTORICAL

In his Yale thesis, DOUGLAS (1960, 1964) systematically brought together all DAM observations, including prediscovery data from 1950, in order to determine the period of DAM rotation and its potential variability over the 10-year interval. This question had been discussed as well by GALLET (1961) on the basis of data in the interval 1951–1957. Douglas' discussion resulted in the adoption by the International Astronomical Union of a conventional DAM sidereal rotation period of 9 hours, 55 minutes 29.37 seconds. The epoch 1.0 January 1957 was adopted at which time the arbitrary radio 'central meridian' longitude coincided with the optical central meridian longitude (System II of the standard ephemerides). This radio longitude is written in the form $\lambda_{\mathrm{III}}(1957.0)$, and represents a central meridian passage (CMP).

4.2. DEPARTURES FROM SYSTEM III (1957.0)

Changes in the radio period were suspected by Gallet, who believed that between 1956 and 1957 the period lengthened by about one second. The adopted period for the entire seven years of data available to him was, however, virtually identical with Douglas' later result.

In 1961 and later years, the data have shown a strong departure from $\lambda_{\mathrm{III}}(1957.0)$ values, the apparent rotation period from 1961 on being about 0.8 seconds longer than the period adopted for the interval 1950–1060. This effect was discovered by DOUGLAS and SMITH (1963), and confirmed by several groups (SMITH *et al.*, 1965; DULK, 1965a). These data represent radio frequencies near 20 Mc/s. The period determination essentially involves a comparison of occurrence frequency as a function of CMP longitude from one year to the next. For small departures, of the order of one second, of the true period from the adopted one, the longitude profiles from one year to the next simply shift without significant change in shape.

4.3. EARLY AND MAIN DAM SOURCES CONSIDERED SEPARATELY

At Boulder a different technique (WARWICK, 1963a) for period determination has been developed alongside the histogram method. The intercomparison of dynamic spectra over a period of time leads to an accurate determination of the rotation. DULK (1967) used this method separately for the early and main sources. As expected, the main source shows the same variations in period as single frequency data. The early source, however, shifts in the opposite sense (see Figure 10).

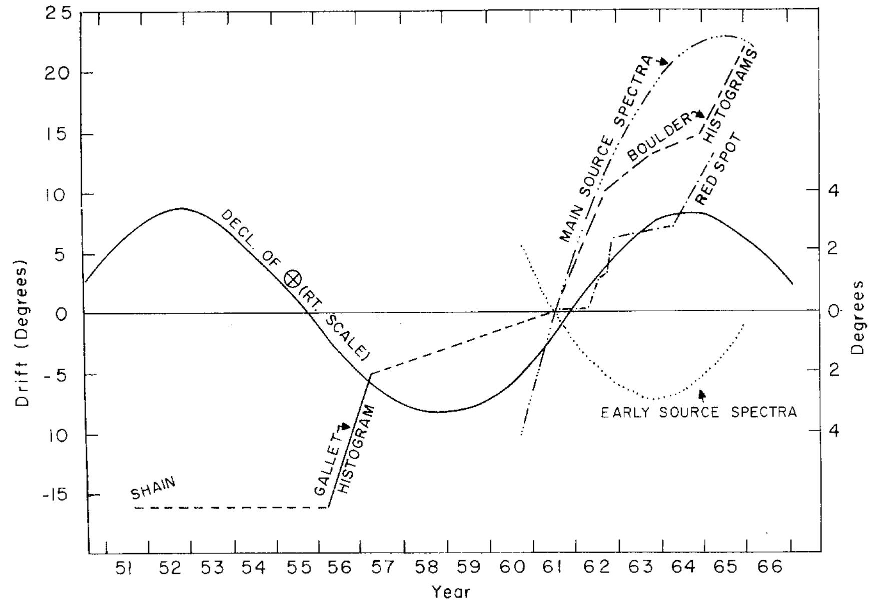

Fig. 10. The drift of DAM with respect to λ_{III} (1957.0), the change of the earth's declination as viewed from Jupiter, and the drift of the Great Red Spot with respect to the conventional System II period (after Dulk, 1967). Shain's data from 1951, and Gallet's data from 1955 through 1957 appear, in addition to Boulder data based both on the spectral landmark method and on the histogram method. By 'drift' is meant the relative (changing) position of a feature of the radio emission plotted as a function of System III (1957.0). In the case of longitude histograms, the most prominent and stable features are the main-source peak of occurrence frequency, and the conspicuous minimum of occurrence frequency that lies just before it. For dynamic spectra, the landmarks are those described in the literature and differ for early source and main source. Figure 10 shows that the position of the radio sources has never been constant in the 16-odd years of data. Gallet's data, and main-source spectra for 1960 through 1965, drift at nearly the same rates. From 1951 to 1956, hardly any observations were made, and from 1957 through 1959, Jupiter emission was rare and the data are less reliable. Therefore, in these intervals we do not know whether there was a uniform drift (as indicated by the dashed lines) or whether a pronounced drift occurred (such as is shown by Gallet's histogram). The main source spectra give evidence of a return to earlier (smaller) longitudes in 1965 and 1966, although the trend is not well established. Early source spectra moved towards earlier longitudes in 1960 to 1964, at the same time that main-source spectra moved towards later longitudes. After 1964, early source spectra moved towards later longitudes, but less rapidly than the main source had moved from 1960 to 1964. The data leave unanswered whether the best representation for the histogram and main source drift is a series of parallel line segments inclined steeply to System III (1957.0) which on the average agree with that system, or is a continuous line oscillating back and forth in a sinusoidal pattern. The Great Red Spot apparently obeys a law of its own, with smaller migrations during the present observation period than have been shown by the radio sources.

4.4. POSSIBLE RELEVANCE OF THE TILT OF JUPITER'S ROTATION AXIS

After preparation of the following section, we discovered an extremely interesting discussion of the same subject by Gulkis and Carr (1966a). Rather than change the section, I have left it stand, and added a review of Gulkis' and Carr's work, in Section .7. Their work was motivated by considerations similar to ours but their results show rather substantial differences.

In Figure 10 there also appears a curve showing the angle between Jupiter's equator and the sight line to the earth (labeled 'Decl. of ⊕'), and a curve of the 1956 and 1957 data of Gallet. The suggested result is that the changes in rotation period may relate to the phase of Jupiter's revolution around the sun. According to our hypothesis, DAM would represent the actual rotation rate only when averaged over the period of Jupiter's revolution. If this is correct, there may be no need to turn to angular momentum transfer between Jupiter's core and outer layers to explain 'variable' rotation. (Long-term changes in DAM and DIM would still, however, permit in principle observations of Jupiter's core rotation; see HIDE, 1966).

4.5. SUNSPOT-CYCLE CORRELATION WITH DAM

Another long standing dilemma has been the negative correlation of emission with the sunspot cycle. The probable existence of the effect was discovered by Gallet in 1957 (GALLET, 1961), and confirmed by SMITH *et al.* (1965). Jupiter's revolution period (11.9 years) is nearly the same as the mean spot period (11.1 years), so that the direct interpretation of a cause-and-effect relation is difficult (see for example WARWICK, 1961; DOUGLAS, 1964; or DAVIS, 1966). The statistical problem is analogous to deciding whether the sunspots are caused by Jupiter, or are intrinsic to the sun. No doubt the spot cycle resides in the sun, but the conclusion depends on the many complete Jupiter revolutions and solar cycles that can be intercompared. DAM has appeared through only about 1.5 solar cycles, which is hardly adequate to distinguish the two effects.

There have always been difficulties in identifying the emission control mechanism. Gallet proposed that increasing uv radiation at spot maximum would increase the electron density in Jupiter's ionosphere, thus cutting off emission. He compared 18 and 20 Mc/s data in an attempt to show a relatively greater decrease in low-frequency emission in 1957 compared to 1956. It now seems clear that his base of only two Mc/s is too small to show the effect. WARWICK (1963a) showed that 30–40 Mc/s occurrences in 1960 were as infrequent as occurrences below 30 Mc/s. This fact seemed to strengthen the case for an ultimate radiation-belt control of DAM.

The conclusion suggested by the complex rotational variations of DAM is that the 'sunspot' effect is really due to the changing geometry of the earth with respect to Jupiter's rotational axis. This idea appears also in DOUGLAS' review paper (1964). The effect was suggested privately to me some six years ago by R. H. Lee, but I considered it unlikely until Dulk's analysis became available. My early point of view depended on the observational data showing the radiation beaming into a cone of semi-angle nine degrees (WARWICK, 1963a). It seemed unlikely that a six degree tilt-angle range could so strongly influence the emission probability. However, further studies of the dynamic spectrum showed that in some instances the beaming was as narrow as five degrees or less (see WARWICK, 1964a).

4.6. DIM'S ROTATION SINCE 1961

The possibility of determining the rotation of the magnetic field in Jupiter's radiation belts came with the measurement of the inclination of the dipole axis to the rotation axis (see Morris and Berge, 1962). Today, data from several observatories confirm that DIM rotates at the System III (1957.0) rate within less than ±0.5 seconds (Roberts, 1965; Roberts and Komesaroff, 1965; Berge, 1966; Barber, 1966; Dickel, 1967). The agreement is a confirmation of the ultimate control of both DIM and DAM by magnetic field geometry. The importance of the result is that DAM's rate established over a decade of data agrees with DIM's, but disagrees in the period since 1961, when DAM's rotation increased in period by one second. The long-term agreement, and short-term disagreement, suggests the importance of the exact position of Jupiter's rotation axis.

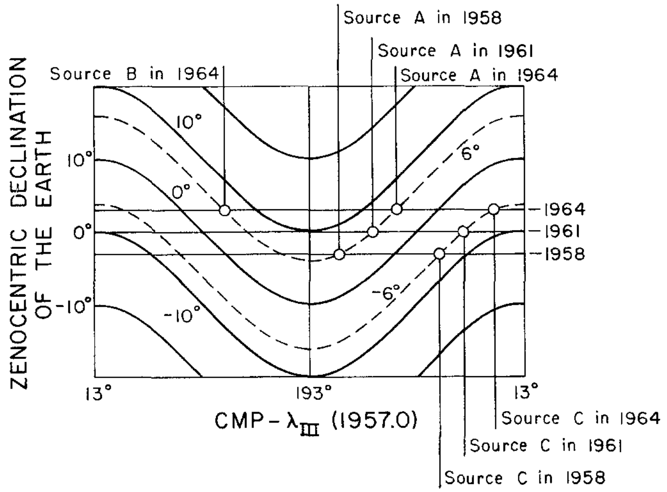

Fig. 11. Graphical presentation of the result by Gulkis and Carr (1966a) on moving sources. This plot is a Cartesian map of the surface of Jupiter, for which equal latitude ranges between ± 20° of latitude occupy equal intervals along the vertical scale. The zenocentric declination of the earth in a given year is a horizontal straight line across this graph, but its ordinate varies over the years between ± 3°; the declination for the years 1958, 1961, and 1964 is shown. Lines of constant zenomagnetic latitude appear as sine curves on the graph. For example, in 1961, when CMP-λ_{III} (1957.0) = 193°, the earth was at zenomagnetic latitude + 10°; at 013°, it was at − 10°. Gulkis and Carr deduced from their data that all the prominent Jupiter sources lie in zones at + 6° or − 6° zenomagnetic latitude. In their interpretation, DAM occurs whenever these zones appear at the subterrestrial point on the surface of Jupiter. As a result of the changing declination of the earth viewed from Jupiter, the sources, at fixed zenomagnetic latitudes, vary in longitudes. As shown by the graph, source C (the late source) is at south 6° zenomagnetic latitude and moves towards later longitudes between 1958 and 1964. Source B (the early source) moves towards earlier longitudes, and source A (the main source) moves towards later longitudes in this same time interval; these two sources lie on the latitude zone at north 6°. The occurrence of emission in 1958 was less frequent than in other years, because the active latitude zones hardly ever were at the subterrestrial point on Jupiter's surface. Gulkis and Carr published data supporting these predicted shifts in position for sources A and C. Figure 10 shows data for the early source that support qualitatively its predicted shift as well. – Objections may be raised concerning this interpretation: (1) Sources A and B are not symmetrically arranged about the 193° meridian as required by the model, nor are they equally frequent in occurrence; (2) Source C is polarized like A and B; (3) There is no early-longitude source similar to source C, except for the rare fourth source described by Warwick (1963a).

4.7. COMMENTS ON THE WORK OF GULKIS AND CARR (1966a)

These authors note that DAM's apparent period may vary sinusoidally as a result of the oscillation of the earth's zenocentric declination. They determine the zenomagnetic latitudes for the main and third sources (sources A and C) required to produce a given longitude shift over the 12-year Jupiter revolution period. Figure 11 shows the proposed geometrical explanation. The main peak (source A) and late peak (source C) shift towards later longitudes between 1958 and 1964. The zenomagnetic latitude along which the radiation is assumed to escape is $\pm 6^\circ$, determined by the observed shifts of the two sources. Unfortunately, Gulkis and Carr do not plot their data for the early source (source B) (but see Figure 10, which shows that the dynamic spectral determination of this source's position is consistent with their hypothesis).

Gulkis and Carr state that the polarization of the third source (source C) is opposite that of the main source (source A), as would be appropriate to a source in the opposite (e.g. southern) hemisphere. However, their data do not seem to bear out this conclusion, inasmuch as left-handed polarization occurs only at longitudes greater than 330° which includes only part of the third source (see CARR *et al.*, 1965a, Fig. 8, reproduced here as Figure 13). In addition, at higher frequencies, SHERRILL (1965) reports almost all radiation (including source C) is right-hand polarized.

Gulkis and Carr use the notation $\lambda_{\text{III}}(1965.0)$ to describe longitudes in a system based on a new DAM rotation period. The period is longer than System III (1957.0) by about 0.3 seconds and follows from the data analyzed with a sinusoidal variation taken into account as explained above. However, it may be premature to adopt a new period. Gulkis and Carr emphasize the agreement between their new value and the value found by BASH *et al.* (1964) from measurements of DIM. This agreement may be fortuitous. In any case, the entire explanation, however attractive it appears at the moment, may be faulty. Crucial tests would appear to be (1) the periodic return of the main source to its 1960–1961 longitude, or (2) its reappearance at the 1960–1961 longitude after its disappearance during the oncoming solar maximum.

5. Solar Correlations

The earth's and, presumably, Jupiter's magnetosphere result from two primary sources: diffusion upwards of ionized hydrogen from the planetary atmosphere, and plasma influx from the solar wind. The solar wind is under control of solar activity; diffusion depends on the kinetic temperature of the upper atmosphere, again modulated by the sun. Some correlation between DAM and solar activity ought to occur under these circumstances.

A short-term correlation with solar activity was initially suggested by KRAUS (1958). Several years later, WARWICK (1960a) and CARR *et al.* (1960) sought to establish the relation with different indices for solar activity. Warwick correlated DAM with large solar radio emission events observed at decametric frequencies, while Carr *et al.* used an index of geomagnetic activity. In 1960, there appeared to be a positive correlation, although it was of marginal significance. DAM was relatively infrequent then compared with the discovery period 1955–1958, or the period since 1960. However, solar activity was rather high then. In the years since, solar activity declined to a low minimum, while DAM increased dramatically. Presumably, this effect accounts for the failure of data of more recent vintage to give an effect (see BARROW *et al.*, 1964 for a fuller discussion and references). That this might be the case was understood at the time of the studies in 1960 (see, e.g., WARWICK, 1960b).

6. Faraday Effect on DAM

6.1. OBSERVATIONAL EVIDENCE FROM THE DYNAMIC SPECTRUM

Electromagnetic waves from Jupiter must pass through the earth's ionosphere to get to our receivers. The ionosphere is a strongly bi-refringent magnetic plasma at decametric frequencies. DAM propagates along two separate paths through the ionosphere, which have different phase pathlengths. The polarization ellipse of the emergent wave is therefore rotated with respect to that of the incident wave.

If we knew the orientation of the emergent ellipse we could introduce independent measures of the properties of the ionosphere, subtract out its effect, and determine the orientation of the incident ellipse. The inverse procedure, common in space and ionospheric research, is to determine the properties of the ionosphere from measures of the rotation on signals of known polarization. The experiments are carried out on moon radar waves, or waves transmitted to earth from artificial satellites.

When a satellite moves across the sky, the radio waves it transmits pass through varying amounts of ionosphere, depending on the distance to the receiving station on the ground. The Faraday rotation varies as a consequence. A close-by satellite signal suffers small rotation, which increases as the satellite moves away. The total rotation along a typical path may exceed 20 cycles at 30 Mc/s. Obviously an equal effect on DAM is to be expected.

In addition to the rotation produced by Faraday effect, there will be rotation resulting from the spinning and spatial translation of the satellite.

Jupiter signals generally are elliptically polarized. Tens of rotations of this ellipse occur in our ionosphere. If we knew the total rotation to better than 10%, we might be able to determine the orientation of the polarization ellipse outside of our ionosphere. Under interplanetary conditions, with electron densities of 10 cm^{-3} and magnetic field strengths of 10^{-4} gauss, the Faraday rotation is minute over the path between the earth and Jupiter. The remaining, and unknown factors in producing Faraday rotation are the electron density and field strength near the source itself. Several estimates have been made of electron densities in Jupiter's ionosphere, and they exceed 10^4 cm^{-3}. Similarly, the field strength surely exceeds one gauss. Therefore, we would expect as much, or even much more rotation near Jupiter than in the earth's ionosphere.

Even if we knew the terrestrial Faraday effect, the rotation produced near the source region might be so large that we would not have a useful result. Two fortunate circumstances made the interpretation of Faraday effect easier than these worrisome factors would seem to permit: (1) The broadbandedness of the Jupiter signals often makes it possible to study the polarization over a two-to-one bandwidth, and (2) the observed orientation of the ellipse in general varies smoothly and systematically over the entire range. As a result, we can combine data from an extensive frequency range to infer the rotation measure as a function of frequency. The measure depends on the integral of electron density times the longitudinal component of the magnetic field.

The Faraday effect appears on radio spectral records as an intensity modulation in frequency, in which the peaks are spaced according to an inverse square law (see Figure 12; also, WARWICK and DULK, 1964; DULK, 1965a; STRAKA *et al.*, 1965; RIIHIMAA, 1966b, 1967). This variation is the same as the variation of the ionospheric Faraday effect.

The Faraday effect on earth satellite signals is not observed in terms of its frequency variation, but rather, the polarization ellipse is observed to rotate at a single frequency. The Jupiter Faraday effect appears as intensity modulation following an inverse-square frequency law; the polarization ellipse stays nearly constant at a given frequency but rotates smoothly as a function of frequency. This phenomenon indicates that

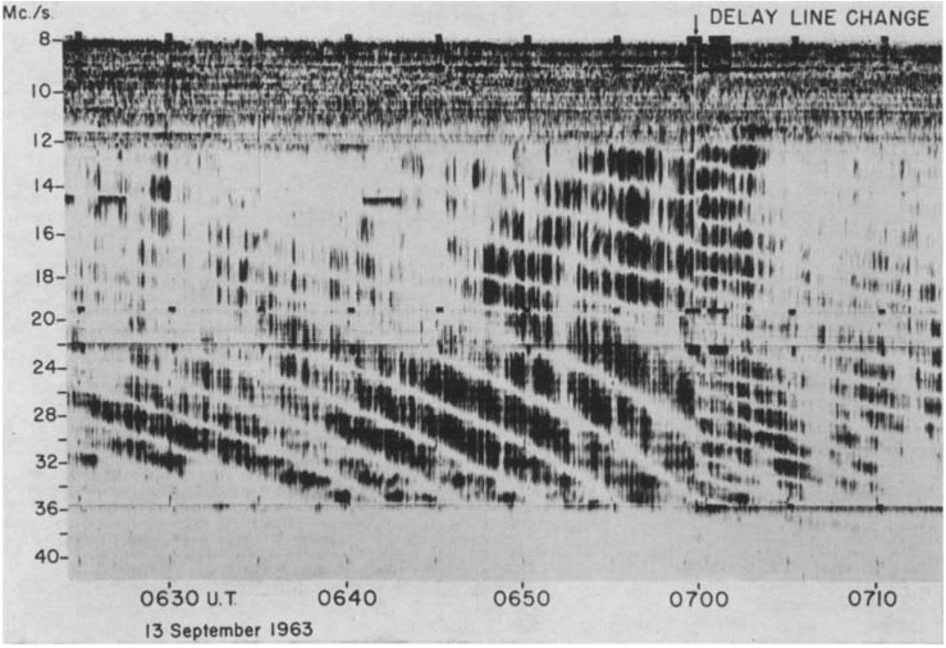

Fig. 12. Terrestrial Faraday effect on DAM (after WARWICK and DULK, 1964). The Faraday fringes appear as a nearly horizontal modulation of the Jupiter emissions. (The sloping white lines across the record are interferometer fringes produced in the equipment.) The Faraday fringes are widely spaced at high frequencies, and narrowly spaced at low frequencies; they are independent of the interferometer fringes. The disappearance of the Faraday effect at low frequencies results from the finite frequency resolution of the equipment.

the polarization at the source remains stable over considerable bandwidths, as much as two-to-one. This fact is a conclusion from the data, and was not anticipated.

For the cases investigated by WARWICK and DULK (1964) the rotation measure derived from the data was, to the very high precision of 10%, entirely due to the earth's ionosphere. Said in another way, the rotation produced near Jupiter was less than $\frac{1}{10}$ that in the earth's ionosphere. This result was also unanticipated.

6.2. INFERENCES ON THE REGION OF GENERATION AND POLARIZATION MODE

Of itself, the fact that DAM often shows a strong elliptical polarization suggests that the source region produces waves oriented similarly throughout its extent. A source large enough to encompass a considerable portion of Jupiter's ionosphere would naturally include Faraday effects from regions differing in field strength and orientation and electron density. The total effect should then include a substantial unpolarized component.

The failure of the expected Faraday effect to occur at Jupiter does not necessarily indicate that the field strengths and densities we used previously were in error. Rather, we inquire under what circumstances would a wave not experience Faraday effect in Jupiter's ionosphere. Perhaps, even, the waves do not pass through Jupiter's ionosphere, though for various reasons this seems unlikely. For example, the stability of the radio spectrum suggests that the radio frequency is intimately tied to the magnetic field strength close to the planet (WARWICK, 1964a). There is also a rapid flipping of the sense of polarization on a very few records that indicates propagation of the signals close to the surface of Jupiter (WARWICK and GORDON, 1965a, b; GORDON and WARWICK, 1967; and Section 8.4).

A more likely explanation is that waves leaving Jupiter lie entirely in a single mode. Since the waves impinging on the earth's ionosphere are elliptically polarized (hence the possibility of observing the terrestrial Faraday effect!) this implies elliptical rather than circular base modes for wave propagation in Jupiter's ionosphere. In the earth's ionosphere, the modes are circular for waves at the frequencies with which we deal. Only under special circumstances, of very restricted extent near the plasma frequency, the gyro frequency, or for directions of propagation nearly at right angles to the field lines, does the polarization become sensibly elliptical. However, the fact that Jupiter waves often are elliptical (SHERRILL, 1965; WARWICK and GORDON, 1965a; GORDON and WARWICK, 1967) implies that these special magneto-ionic conditions are somehow satisfied. Given the very wide range of longitudes over which DAM is visible, we conclude that the angle of propagation must vary considerably. Also, since Jupiter's ionosphere is produced like ours, by solar uv ionizing flux, the plasma frequency must vary. Therefore, it seems unlikely that either the direction of propagation or the electron density gives the special conditions for elliptical polarization.

The one parameter that appears to satisfy the conditions is the electron gyro frequency. If the wave and gyro frequencies are close to one another, the modal polarization remains elliptical over a wide range of angles. The orientation of the modal polarization ellipse depends on the direction of the projected magnetic field at the point where the waves leave the ionosphere of Jupiter. If the major axis of the ellipse is parallel to the projected field, the mode in general is the ordinary mode; a perpendicular axis implies the extraordinary mode. From the spectrographic measurements of the terrestrial Faraday fringes, we can very nearly infer the orientation of the ellipse impinging on our ionosphere (Warwick and Dulk, 1964). Such a measurement can identify the mode of the radiation leaving Jupiter. On this basis, Warwick and Dulk suggested that the mode was the extraordinary mode; this important result badly needs confirmation.

7. DAM's Polarization as a Function of Longitude and Frequency

7.1. High DAM frequencies

At frequencies greater than 18 Mc/s, the polarization remains dominantly right-handed elliptical at all longitudes (Barrow, 1964a; Sherrill, 1965). The axial ratio is about two-to-one. The orientation of the major axis appears to be at right angles to the magnetic field, that is, at right angles to Jupiter's rotation axis (Warwick and Dulk, 1964). There are events in which the polarization rapidly flips from one circular sense to the other (Sherrill and Castles, 1963; Sherrill, 1965). Even in these events, the dominant sense is right-handed. These will be discussed further in Section 8.4. The presence of a single polarization sense at all longitudes was one of the leading factors in the suggestion that Jupiter's dipole was displaced into the southern hemisphere (Warwick, 1961; 1963a, b).

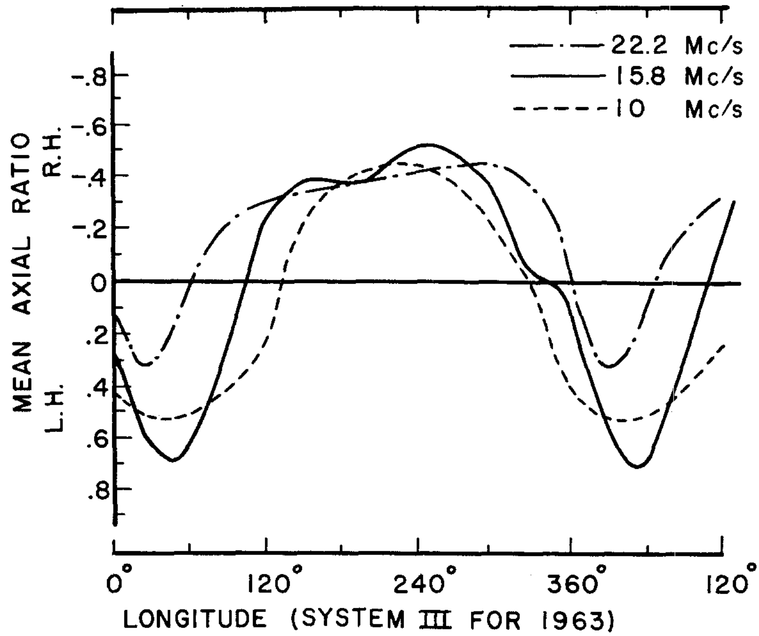

Fig. 13. DAM's polarization as a function of radio frequency and longitude (after Carr *et al.*, 1965a). At low frequencies the variation of polarization with longitude becomes nearly symmetric.

7.2. Low DAM FREQUENCIES

The polarization at frequencies less than 20 Mc/s is frequently left-handed (Dowden, 1963). For example, Figure 13 (Carr *et al.*, 1965a, b) shows nearly as many left-handed as right-handed events at 10 Mc/s. The early source region up to λ_{III}(CMP) $= 100°$ to $150°$ is predominantly left-handed. In general, the low-frequency occurrence frequency and polarization is symmetric as a function of longitude.

7.3. Origin of low frequency DAM

Ellis and McCulloch (1963) suggested a model in which the emission source lies at some distance from the surface in a region where the magnetic field varies symmetrically in longitude. Stone *et al.* (1964) suggested on the basis of very sensitive observations at 26.3 Mc/s that even at high DAM two separate mechanisms might operate, one of which produces low-level persistent emission widely scattered in longitude, and the other produces the familiar intense emission. They suggested also the possibility that different radiation belts were effective in the two kinds of emission. Figure 14 shows dynamic spectral events of a long enduring kind that may be the type of emission observed by Stone *et al.* These events have not always been visible in our data, although we observed them in 1960 (Warwick, 1961). Gruber (1965) proposed, on the basis of the frequency of occurrence of DAM through a typical apparition, that the magnetospheric tail of Jupiter might account for the great reduction of events late in the apparition relative to early in the apparition. However, this reduction of events may be because events observed before local midnight (i.e., late in the apparition) suffer greater ionospheric absorption in the earth's atmosphere, and greater interference from terrestrial telecommunications. We suspect these factors are quite important in determining the number of observed Jupiter events.

8. High Time Resolution Studies

8.1. Polarization flips

Franklin and Burke (1958) reported cases where the sense of the polarization varied rapidly from right to left and back. In 1962, Dowden observed bursts with an oscillograph, and has published records showing changes from one state to the other on a time scale of a few seconds (Dowden, 1963). Similarly, Sherrill and Castles (1963), Barrow (1964a), and Sherrill (1965) found a few events where the sense of polarization varied rapidly during periods when the emission showed complex burstiness on a time scale of seconds.

Sherrill (1965) points out that these effects could result from scintillation within the earth's ionosphere. The ray paths of the two ionospheric propagation modes may differ by several kilometers, even at high DAM. If the two rays encounter random, independent fine structure along their separate paths, they may well scintillate independently and produce the observed flips from one state to the other.

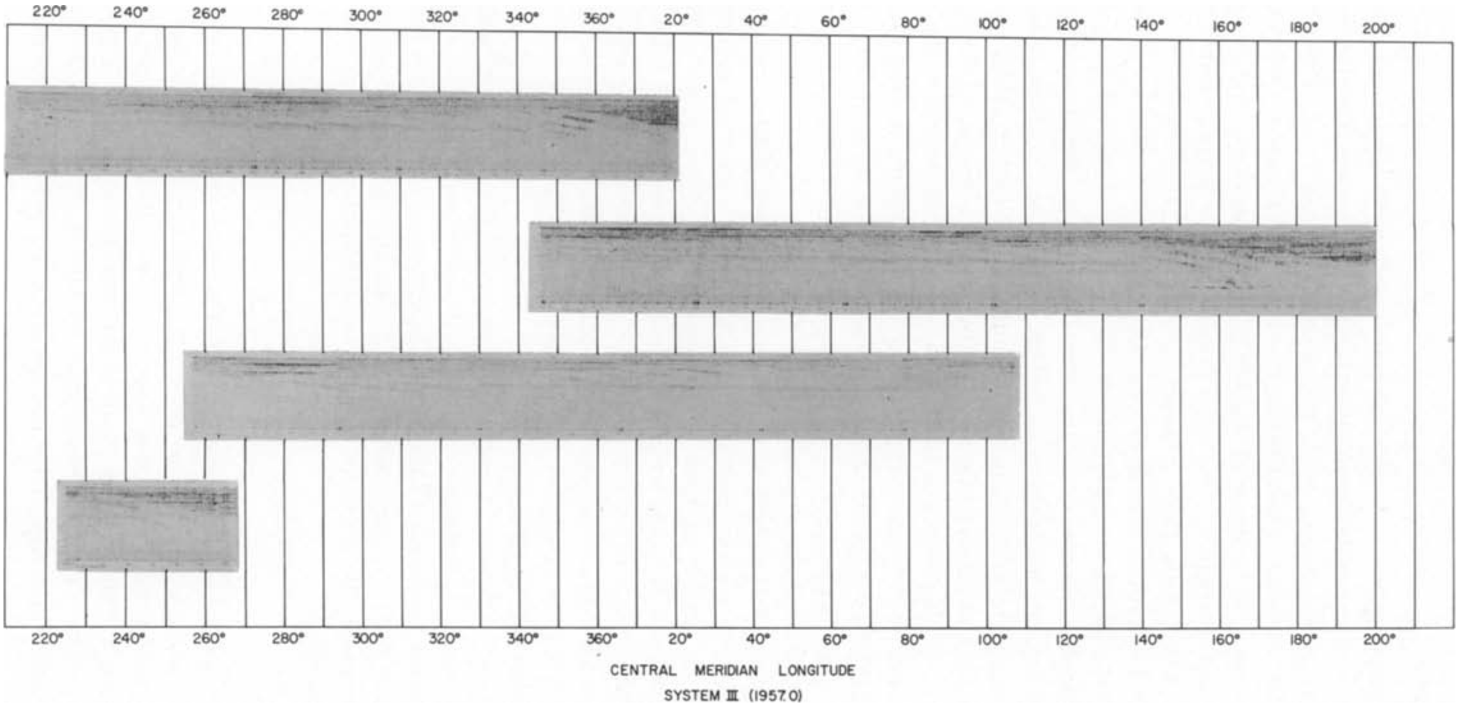

Fig. 14. Very steady, long-enduring low frequency decametric emission from Jupiter. *These data were recorded by the Boulder radio spectrograph.* Because of the low intensity, the emission appears most readily if you view the spectra obliquely from the direction of the longest dimension. There was continuous emission for many hours on each of these nights. No sharply defined Io position is involved except for one night when the early source appeared. This type of continuum appears only at low decametric frequencies, less than 20 Mc/s, and was observed also in 1960 (WARWICK, 1961).
These nights occurred in group near the middle of September 1965, when geomagnetic activity, as measured by the planetary A-index, was low.

8.2. INTERFEROMETRY

In recent years strong evidence indicates that some bursts with time scales of a few seconds or less are due to scintillations in interplanetary space away from the vicinity of the earth (DOUGLAS and SMITH, 1961; SMITH and DOUGLAS, 1962; HEWISH and WYNDHAM, 1963; HEWISH *et al.*, 1964; COHEN, 1965; SLEE and HIGGINS, 1966; COHEN, *et al.*, 1967; SALPETER, 1967; SMITH *et al.*, 1967). Ionospheric scintillation theory developed further, and observations were made of the dynamic spectra of scintillations (WARWICK, 1964b; MASUMOTO, 1965; YERUKHIMOV and RYZHOV, 1965).

DOUGLAS (1963, 1964) found that DAM receivers spaced over baselines of 100 km often received virtually identical bursts, but with occasional time shifts of the order of one second. Interpreted as ionospheric in origin, these bursts imply structures on a scale of the order of 1000 km, moving at speeds of 500 km$\cdot$sec^{-1}. There is ample independent evidence that ionospheric patterns drift at much slower speeds, of the order of 100 m$\cdot$sec^{-1}. Douglas also showed that the sense of the drifts reverses at the time of Jupiter's opposition. He hypothesized that the source of scintillations is the interplanetary medium. Before opposition, Jupiter is seen in the morning sky and the solar wind blows plasma clouds out towards Jupiter that are seen moving from east to west; after opposition, Jupiter is seen in the evening sky and the wind blows from west to east. Thus the sense of the drifts reverses at opposition.

SLEE and HIGGINS (1966) carried out extremely wide-based interferometry, over spacings of the order of 10^4 wavelengths at 19.7 Mc/s. They observed pronounced interference fringes for periods of minutes even on these baselines. There was some reduction in fringe amplitude at the longest baselines, indicating that the source was nearly resolved. The corresponding size is about 3″ to 5″. However, they (and SLEE, 1966) inferred that interplanetary scintillation had broadened the source to the observed size, and they considered they had set only an upper limit to the size, which might be considerably smaller than 1″.

Stable fringes exist for periods of several minutes, and this implies that the source remains fixed in position at least this long. The source is stable on a scale much smaller than the planetary diameter (about 40″). Unfortunately, the precise location of the source cannot be determined because the fringe number and the amount of refraction are unknown. The apparent position of DAM therefore has not been experimentally determined.

8.3. SPECTROSCOPY

RIIHIMAA (1964a, b; 1966a, b, c) measured the dynamic spectrum of DAM on a time scale of 0.1 seconds, and over two Mc/s sweep width. On this time scale, the bursts are complex with both narrow and broadband structures. Slow, drifting emission, lasting several minutes, were seen to be made up of many fine time structures. Riihimaa's receivers were of two kinds: (1) multiple channels set side by side and photographed on a single film, and (2) swept frequency recorded on an intensity-modulated oscillograph beam.

Using a receiver originally designed by Riihimaa for solar studies, and now modified for Jupiter, WARWICK and GORDON (1965a) and GORDON and WARWICK (1967) made simultaneous measures of the emission polarization and spectrum over the frequency range of 24 to 37 Mc/s on a time scale of 10 milliseconds. We determined all parameters of the polarization (axial ratio, sense of rotation, orientation of the ellipse, and the power in the unpolarized as well as the polarized radiation). Most of the records (about 90%) showed no variations on a scale shorter than about one second, and most bursts lasted for tens of seconds (decasecond bursts). The remaining records showed variations on a scale of 10 milliseconds or perhaps somewhat shorter.

In the case of decasecond bursts ('L' pulses in Gallet's nomenclature) the emission was often broadband (several Mc/s) in the interval from 24 to 37 Mc/s. Emission

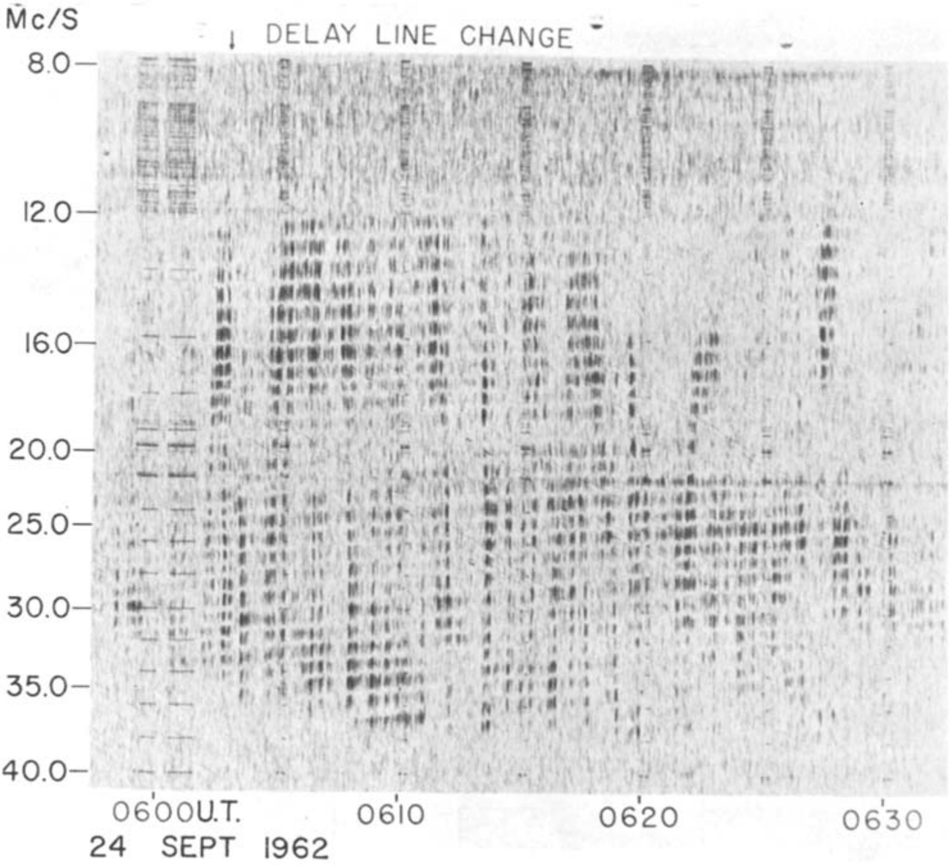

Fig. 15. Broadband bursts in DAM. A portion of early source emission is shown in which bursts of fairly long duration cover more than one octave in frequency. By holding this figure obliquely so you sight across it in the frequency direction, you can see the many complex shifts in time of occurrence of single bursts as a function of frequency. There is a region at about 20 Mc/s in which the equipment has relatively low sensitivity. This appears as a band in which there are relatively few bursts, although the strongest still survive there.

drifting in frequency on a time scale of a few seconds or a minute also occurred. Riihimaa had earlier observed bursts drifting at this rate. Such bursts often show conspicuously on the Boulder spectral records (WARWICK, 1963a). Figure 15 shows an example of the latter which contains many bursts lasting only a few seconds. Each of the bursts is very broadband, covering a frequency range of two or three to one. Figure 16 shows a similar kind of burstiness appearing on records of solar emission; these bursts may have an origin similar to the Jupiter bursts.

It seems quite clear that the mechanism that produced these bursts is of a different nature than so far proposed for interplanetary scintillations. The established theory of scintillations in the earth's ionosphere does not explain scintillations seen with radio spectrographs (WARWICK, 1964b).

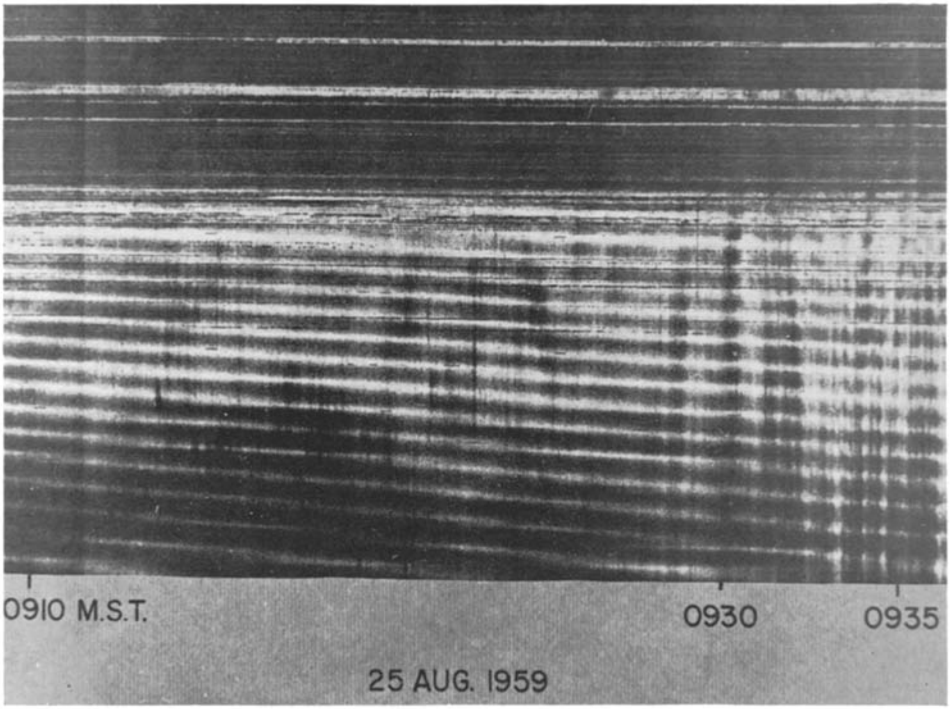

Fig. 16. Near 0935 MST (1635 UT), there are broadband solar bursts strongly reminiscent of the Jupiter bursts shown on Figure 15. The solar bursts are of comparable bandwidth, and also exhibit complex shifts in frequency with time. At higher frequencies, emission during this solar event is known to have arisen from particularly small sources. This fact also suggests the intercomparability of the solar and Jupiter events. In view of their very wide bandwidths, interpretation in terms of multiple scattering appears very difficult.

The polarization structure of decasecond pulses exhibits the terrestrial Faraday effect as was earlier observed in Boulder (WARWICK and DULK, 1964). In a few cases, during decasecond pulses, there occurs isolated fast structures, no more than once or twice an hour of recording. For details of their appearance, see GORDON (1965).

Millisecond pulses ('S' pulses in Gallet's usage) are of special interest. They have now been measured for polarization and frequency drift characteristics. Their most striking feature is their great intensity. Gallet noted this aspect of the short bursts on equipment having a rather long time constant, .01 seconds. We estimate that millisecond bursts are more powerful than decasecond bursts by a factor of the order of 100. The basis for this factor is the comparison of the same emissions observed in Boulder on equipment with a one second time constant and at Arecibo with the fast radio spectrograph described above. In Boulder the bursts have moderate intensity unresolved in time; at Arecibo, they are very intense, with an estimated one to one-hundred duty cycle.

A second noteworthy characteristic of the millisecond pulses recorded on 17 October 1964 at Arecibo is their negative drift in frequency, at the very fast rate of 20 to 30 Mc/s^2. They are also very narrowband, no more than several hundred kc/s and perhaps much less. The equivalent brightness temperature of the bursts, if they subtend five seconds of arc, is perhaps 10^{14} to 10^{15} °K, 100 times the 10^{12} °K temperature of the decasecond bursts (BURKE, 1961). To my knowledge there is no more intense natural radio source at this frequency.

These millisecond bursts vary in polarization as a function of frequency. Imagine the spectrum of a single, isolated burst represented by beads on a string, large beads indicating intense emission. Suppose the color of the beads represents the state of polarization, right-handed (red) or left-handed (lavender). If the state of polarization were a right-handed ellipse at all frequencies, the beads would be reddish purple and of uniform size. This is the case for decasecond pulses. For a millisecond burst, the beads alternate, big red ones, and little lavender ones.

Groups of millisecond pulses were observed at Arecibo on several occasions. Their similarity from burst to burst is unexpected, and the bead-on-a-string analogy may help describe the situation. From one burst to the next, there is a strong tendency for the size and color of the beads to be the same. That is, the polarization often remains constant from burst to burst at a given frequency. After 0.1 seconds or so, the position of a given bead may shift systematically to either higher or lower frequencies. This behavior may explain why slower recordings of burst polarization at a single frequency sometimes show a flipping of the state of polarization. (The possibility that ionospheric scintillation could produce the effect was noted earlier.) A rapid sequence of these millisecond bursts would lead to a 'purple' bead pattern if it were observed with a conventional, slow polarimeter.

The Arecibo polarimeter operated over too narrow a band to detect the low-frequency cut-off of the Jupiter bursts. The best developed case is sharply limited on the high-frequency side (at 28 Mc/s). This upper limit also shows clearly on simultaneous records in Boulder.

One other case at Arecibo is important insofar as it tends to establish that the very fast bursts are produced at Jupiter in the source region, and not in interplanetary space or the earth's ionosphere. There is smooth emission, with no variability on a 10 millisecond scale, which occurs simultaneously with millisecond bursts. The latter appear superposed on a background of this smooth emission. The smooth structure lasts for only a few minutes, after which the event consists entirely of millisecond bursts. A similar situation may have existed in the records that Gallet and Bowles obtained in 1956 and 1957, as was discussed by GALLET (1961). He noted that "one may even receive S-pulses on one frequency and L-pulses on the other" (the frequencies were 18 and 20 Mc/s).

The existence of extremely fast frequency drifts and of narrow bandwidth is consistent with Gallet's remark that "the dynamic spectrum of the pulses must be very narrow". However, the rapid frequency drift may account for his failure to detect the correlation of pulses on fixed-frequency receivers two Mc/s apart.

8.4. ORIGIN OF MILLISECOND PULSES

The early observers (GALLET and BOWLES, 1956; KRAUS, 1956, 1958) did not clearly state whether they measured the peak intensity of millisecond bursts. Gallet reported that they were of very great intensity (unpublished), but his published records were made with a high-speed pen recorder. The response time was probably not fast enough to permit the pen to rise to full amplitude before the burst level fell off. KRAUS (1958) published oscillographic recordings made from magnetic tape; his illustrations do not permit an estimate of intensity. Lacking a better estimate, we shall take the value obtained above: 100 times greater than for decasecond pulses.

In polarization and frequency, millisecond bursts are similar to decasecond bursts. Their distinguishing features are their bandwidth, drift, and shortness of duration. These features are consistent with decasecond bursts, if we hypothesize that the total energy involved in millisecond bursts is the same as in decasecond bursts. The difference between them would then be a matter of the beaming of the radiation. The bursts then relate to the same basic physical mechanism, which produces intense short-lived millisecond pulses in one configuration and relatively feeble decasecond bursts in another.

We hypothesize that one mechanism produces decasecond and millisecond bursts. The smoothness or size of the region over which the bursts are generated determines whether one or the other appears. The smoothness might be a secondary feature of the conditions at the planet.

We saw above that the brightness temperature of the millisecond bursts may be as high as 10^{14} or 10^{15} °K. We believe that no individual radiating particles at Jupiter have energies $E = kT_B = 1$ GeV (decasecond bursts), let alone 100 GeV (millisecond bursts). In consequence, the radiation mechanism involves coherently radiating electrons and protons. We believe it highly plausible to suppose that millisecond pulses represent radio-frequency phase coherence on an abnormally large scale (WARWICK and GORDON, 1965a; GORDON and WARWICK, 1967). The decasecond pulses involve the same radiating region incoherently excited (local coherence must also exist for these bursts). No difference in the energetics or radiation mechanism is assumed to exist for millisecond bursts, only the smoothness and coherence of the emitting region (a region comparable to Jupiter's size).

Kraus (1958) considers another model for millisecond bursts. Its leading feature depends on his belief that these bursts occur in pairs or triplets, and thus may involve echoes. A burst originating below Jupiter's ionosphere propagates to the earth along several paths involving reflections between Jupiter's ionosphere and surface. We shall not consider the model further, only because the best example we have of millisecond bursts (17 October 1964, see Warwick and Gordon, 1965) does not exhibit the echo phenomenon.

Regardless of whether the burst is of short or long duration, the emission sources produce a beam of the order of a few degrees of arc in dimension. This conclusion rests on two kinds of evidence: direct interferometry of the source size (see Section 8.2), and the time structure of the dynamic spectrum (Warwick, 1964a). The latter implies that the beamwidth is three to five degrees, a smaller dimension than established by direct interferometry. Beaming on this scale occurs for all types of Jupiter emission, in the slowest variations, such as the decaminute bursts observed at superior conjunction by Shain (1956) and Warwick (1962), as well as decasecond and millisecond bursts. We shall assume that the basic emission pattern of any small volume of the source is a cone with a semi-angle of about three degrees.

The size of the 'source' follows somewhat indirectly from the spectral data. Jupiter rotates about 36° per hour. Some dynamic spectral features last for about 10 minutes and appear repeatedly at the same longitude. Thus the feature is seen for 6° of rotation. Alternately, a source covering a range of longitude on Jupiter of as much as 6° can radiate towards the earth simultaneously. The implied zenographic extent of the source on Jupiter's equator at the central meridian would be about $(6°/57.3°) \times$ one Jupiter radius $= 0.1$ radius $= 2.3''$.

We assume that decasecond or decaminute bursts occur when a region of this extent, about 7000 km, is incoherently activated. The sum of all the emission is elliptically polarized, representative of the averages of the magnetic field and plasma conditions taken over the active region. Millisecond bursts occur when the same region is coherently excited. The total emission is again elliptically polarized but two further effects may occur: the intensity of the emission becomes very great in the preferred directions for which the waves from large portions of the source add in phase, and there will be an observable Faraday effect produced in Jupiter's ionosphere.

Coherence over this large source implies that the primary beam, a cone of three degrees semi-angle, will itself be split into a number of elemental beams each of which subtends a characteristic angle (λ/7000 kilometers) radians, where λ, the wavelength of decametric emission, is .01 kilometers. This angle, one-third second of arc, is carried across the direction to the earth in about ten milliseconds. The combined energy of the elemental beams is about the same as is normally emitted by decasecond bursts. If there is a very smooth plasma layer in Jupiter at this time, the difference in path length between the characteristic magneto-ionic modes (base modes) will be small from one point in the source to another. When the wave frequency is, as appears to be the case at Jupiter, close to the electron gyro frequency, the base modes are counterrotating, orthogonal ellipses. An arbitrarily polarized wave splits into a wave in each of these base modes, which propagate independently through Jupiter's ionosphere. The superposition of the waves afterwards produces alternating circular polarization at alternating frequencies. If the plasma layers of Jupiter's ionosphere vary from point to point, then there will be a tendency towards depolarization, and the Faraday effect at the gyro frequency (the Y-one Faraday effect) could not be recognized. This Faraday effect, when it is present, permits a determination of the magnetic field strength and electron density above the source. On one occasion, we obtained the values $B = 14$ gauss and $N_e = 4 \times 10^4$ cm^{-3} (WARWICK and GORDON, 1965a; GORDON and WARWICK, 1967).

RIIHIMAA (1967) showed that short duration pulses tend to occur more frequently in the early source, which is excited by Io at 90°, although short pulses are relatively infrequent even then. This result was confirmed by OLSSON and SMITH (1966), BAART, BARROW, and LEE (1966), and BARROW and BAART (1967). The millisecond structures analyzed by WARWICK and GORDON (1965) also were from the early source.

8.5. INTERPLANETARY AND TERRESTRIAL SCINTILLATIONS

The earliest observations of DAM clearly showed the importance of modulation by the earth's ionosphere. There has been considerable discussion ever since about how one distinguishes this modulation from the characteristics of the source at Jupiter.

Terrestrial radio star scintillations suggest that the decasecond structure, and variations on a scale of only fractions of one second, may be produced locally, near the earth and in its ionosphere, or perhaps in interplanetary space. Millisecond pulses do not seem to occur on radio stars, even the smallest ones that are most sensitive to scintillations. For this reason alone, we might conclude that they are a source phenomenon. The same conclusion was reached above on the basis of the simultaneous appearance of millisecond and decasecond bursts.

Jupiter emission has long been suspected of coming from very small sources. BURKE (1961) was the first to suggest that the size of the source could be estimated from a measurement of the rate of scintillations on a sequence of small radio sources of known size. This technique is currently used to determine the size of very small radio sources (quasars at decimetric frequencies; see COHEN *et al.*, 1967).

The distance to the irregularities is difficult to measure from radio-star scintillation observations, and the procedure is generally indirect. Strong correlations in DAM are present over baselines even for short-lived structures. This seems like a decisive argument in favor of a scintillation screen lying at distances large compared with 100 km.

WARWICK (1966) suggested that the variations on DAM at superior conjunction may represent the basic time variations of the source at Jupiter. He called them decaminute bursts since the variations are slow, on a time scale of minutes or even tens of minutes. Faster bursts, produced by the scintillation mechanism, would then be suppressed as a result of the increased angular size of Jupiter seen through the corona (WARWICK, 1962).

9. Physical Theory of Origin of DAM

Most researchers identify DAM's frequency with the electron gyro frequency. Their reasons have been either theoretical or observational, or in some cases, both. HIRSCHFIELD and BEKEFI (1963), ELLIS and MCCULLOCH (1963), and MARSHALL and LIBBY (1967) had specific mechanisms in mind that produce gyro radiation, or frequencies close to it. ZHELEZNIAKOV (1958) suggested emission at the plasma frequency; in a recent paper (1965) he has modified the earlier results to include the effect of a magnetic field, and finds emission will be at the gyro frequency for sufficiently low plasma density. BURKE and FRANKLIN (1956) proposed that propagation effects through a magneto-ionic medium indicate the emission occurs near the gyro frequency. All waves and polarizations would be created below the Jupiter ionosphere, but only some could escape. WARWICK (1963a) concluded that the emission is at the gyro frequency because of the stability of the dynamic spectrum. He also (1961) pointed to the existence of singularities in the dispersion relation which favor generation of emission near the gyro frequency. None of these explanations is in any sense complete.

CHANG (1963) discussed whistler interactions with trapped particles as a mechanism for precipitation of electrons from Jupiter's magnetosphere. An anisotropic electron distribution is required for amplification, and the resulting whistler emission is highly directional, parallel or antiparallel to the magnetic field. A similar discussion (KENNEL and PETSCHEK, 1966) of dumping in the earth's belts led to an upper limit on the trapped particle flux in the magnetosphere.

We now take for granted that a magneto-plasma exists near Jupiter; its density and the precise value of the field are in question. Values comparable to those in the earth's magnetosphere and ionosphere serve as an approximation. Within such a plasma, there are energetic electrons and protons and hydromagnetic waves of various kinds. Gradients in field strength, plasma density, and particle streaming couple different wave modes to one another. With so many possibilities, theory must be strongly guided by observation.

One of the most detailed theories (ELLIS, 1965) depends on the existence near Jupiter of helical electron beams imbedded in a magneto-ionic plasma. The dispersion relation for plane waves in this medium was discussed by ZHELEZNIAKOV (1959; 1960a, b), NEUFELD and WRIGHT (1964), and recently by FUNG (1966a, b, c). Solutions with the propagation vector at an arbitrary angle to the magnetic field were given by Fung; the other authors restricted themselves to the less complicated, though still far from simple, cases of longitudinal or transverse propagation.

Plane waves grow in amplitude at frequencies near the gyro frequency. These waves are refracted in an ionospheric plasma, so that the helical beam of electrons does not significantly change the energetics of the medium. The power in DAM follows from all electrons in a 'bunch' radiating phase coherently. In Ellis' theory the power radiation pattern of the bunch is identical to each electron's individual power radiation pattern. The latitude distribution of bunches gives the longitude profile of DAM at low frequencies. Departures of the zenomagnetic dip angle from its value for a planet-centered dipole field determine the emission profile at high frequencies. The departures range up to 18° at the latitudes producing 28 Mc/s radiation. They would probably be still higher at 39 Mc/s. (Variations as large as 25° occur locally, over 30° to 40° of terrestrial longitude in the region of the South Atlantic 'anomaly'; see CHAPMAN and BARTELS, 1962).

Ellis also obtains values for the electron density within about one radius of Jupiter's surface. His electron density profile has a slow decay with height, with densities of 10^5 cm^{-3} at one radius above the planet. The velocity distribution of the electrons is twofold: (1) a high-energy component with a delta-function pitch angle distribution, and (2) a low-energy component with an isotropic pitch angle distribution. ZHELEZNIAKOV (1965) emphasized that the electron motions are basically incoherent in Ellis' theory. A wave cannot grow to too large an amplitude within the plasma without violating the physical basis of the dispersion relation. This limitation has been explicitly recognized by FUNG (1966c). At the time of DAM the plasma may sustain strong enough coherent electron oscillations to alter the strength, direction, and frequency of emission. BRICE (1963) also emphasized the importance of accounting for coherency among the electrons. His critique was directed explicitly towards DOWDEN'S (1962) theory of Doppler-shifted cyclotron radiation (which has a close generic relation to Ellis' theory), and stands as a fundamental, although essentially theoretical objection to Ellis' interpretation.

Let us estimate the wave energy density in DAM at Jupiter in an event with a total power of $W = 10^8$ watts. Many researchers have quoted much larger values, 10^{10} or 10^{11} watts, but a somewhat smaller value, 2×10^7 watts was derived by WARWICK (1963a) and accepted by DOUGLAS (1964). The energy density in the region of generation is $u_1 = W/(vA)$, where v = the group velocity, and A = the area of the source. Assuming that $v = c = 3 \times 10^{10}$ $\text{cm} \cdot \text{sec}^{-1}$ and $A = 10^4$ km^2 (a conservative estimate), we find $u_1 = 3 \times 10^{-14}$ $\text{ergs} \cdot \text{cm}^{-3}$. The beam of radiation spreads over a solid angle of about .01 steradians (corresponding to beaming within 6°). Within a distance s_1 of the source, where $\sqrt{.01} s_1 = 10^4$ km, the energy density has the value $u_1 \lesssim 3 \times 10^{-14}$ $\text{ergs} \cdot \text{cm}^{-3}$. Outward from s_1, the energy density falls slowly from this value. At distance s (where $s \gg s_1 = 10^5$ km), $u(s)$ is $u = u_1 (s/s_1)^{-2}$. Thus $u = 3 \times 10^6 s^{-2}$ where s and u are in c.g.s. units. For comparison, near a one-watt transmitter operating into an antenna of 10^2 m^2 cross-section, the energy density is 3×10^{-10} $\text{ergs} \cdot \text{cm}^{-3}$. Transmitters with this power flown within the earth's ionosphere appear to act in a non-linear manner and generate waves in all basic modes. We may surmise that DAM is also energetic enough to produce strong non-linearities.

Spectral observations of the flux density variation with frequency differ from the observations of Ellis (ELLIS, 1965, Fig. 16). Ellis shows a monotonic decrease in flux density from low frequencies up to about 28 Mc/s, with flux densities less than 10^{-24} $\text{watts} \cdot \text{meter}^{-2}$ $(\text{cps})^{-1}$ at frequencies greater than 28 Mc/s. However, dynamic spectra show that when Jupiter emits DAM towards the earth, its flux density exceeds 10^{-21} or even 10^{-20} at frequencies as high as 39 Mc/s. High frequency emission is narrow-band, and occurs only when the Io–Jupiter geometry is 'right', as discussed earlier. On a spectral plot such as Ellis', this emission should appear as a monochromatic spike. A theory must explain this kind of spectrum, rather than a monotonically decreasing spectrum. The spectrum as Ellis plotted it has significance in a complicated sense involving averages over inactive periods and all Jupiter longitudes (McCulloch and Ellis, 1966). Ellis also computed synthetic dynamic spectra for the 'early' source (Jupiter emission in the longitude range 80° to 160°). His spectrum contains a number of details looped towards high frequency, whose envelope produces the positive drift profile of early-source emission. These loops represent the locus of emission seen emanating from a particular magnetic anomaly in Ellis' model of the magnetic field. These anomalies produce first positive and then negative drifts in frequency with time as they pass by the line of sight to the earth. Although the dynamic spectra of the early source do show complex details (see Warwick, 1964a), they are not of this character.

Finally, Ellis derives a schematic dynamic spectrum exhibiting structure on several time scales: tens of minutes, seconds, and milliseconds. He indicates that the long lasting structures are composed of millisecond bursts. It would be safe to infer that his theory predicts such bursts, whose random superposition into burst-groups finally results in a normal event. As we have discussed, fine-structure events are of very great intensity compared with normal events. Whatever produces them, coherence or some entirely different phenomenon, they do not simply merge together.

Ellis indicates that the drift rate of millisecond bursts is due to electron bunches traveling in Jupiter's magnetosphere and emitting gyro frequency radiation. Drifts from high to low frequency are due to emission from bunches traveling outward after they mirrored. The following discussion is my inference, and is not presented in his paper. Consider radiation near the gyro frequency emitted by electrons spiraling around lines of force. The electrons move away from Jupiter's surface into the magnetosphere. The local gyro frequency decreases as the electrons move into weaker and weaker fields. The gyro frequency f_L varies with time as $1/f_L \, \mathrm{d}f_L/\mathrm{d}t = 3/(R/v)$ where v is the electron velocity along the line of force and R is the distance of the electron from the dipole. (This formula assumes that the motion is along a practically radial line of force near the pole.) At 0.2 c, a particle would experience $\mathrm{d}f_L/\mathrm{d}t = 75 \text{ Mc/s}^2$ near the surface, a value close to millisecond-burst drift rates seen at Arecibo. The high intensity and complicated polarization of the observed bursts show that this model is probably oversimplified in essential ways, but it seems to be consistent with Ellis' hypothesis. However, the ad hoc assumption of exciting particles moving away from the surface is unlikely, since the bulk of precipitating particles will be absorbed by Jupiter's atmosphere rather than mirrored.

Another theory of DAM was proposed by me (Warwick, 1961, 1963a). This has become known as the 'Cerenkov theory', although this is a misnomer. The singularities of the magneto-ionic dispersion relation are likely to be involved in the emission because they represent waves with phase velocities slower than light. Cerenkov emission involves a singularity near the gyro frequency, and was therefore suggested as a possibility. On phenomenological grounds, it appears that the emission takes place along the lines of force whether or not it is Cerenkov emission. This conclusion depends on the fact that emission generated over a large area and beamed into the plane perpendicular to the magnetic field would be visible over a wide range of longitudes, and this is inconsistent with the observed extremely narrow longitude beaming shown by dynamic spectra.

The main feature of my theory was that DAM originates near the surface of Jupiter. Only in this way did it seem possible for the narrow-band dynamic spectral features to appear precisely (within a few degrees) and repeatedly at the same longitude. This location of the emission (see WARWICK, 1964a, for a more extensive discussion) renders it impossible for emission beamed along the lines of force to reach the earth if the field is a planet-centered dipole. In fact, emission can hardly reach the earth even after reflection from the planet's ionosphere or from its surface. For this reason, I introduced a grossly-displaced dipole as the source of the field. It was possible to find a position of the dipole that would fit tolerably well the observed emission pattern.

However, the model needs updating for several reasons. In the first place, the assumption that only precipitating particles were involved in the emission appears too restrictive. Especially in view of the Io modulation, it seems that hydromagnetic waves can play a role. Secondly, the premise that L-shells between 1.5 and 3 planetary radii are involved may not properly account for the Io-connected emissions. Even the displaced dipole model of the field does not explain how an L-shell of 6 radii (Io's position) generates emission towards the earth unless the source of excitation crosses to smaller L-shells, or a radically modified field (containing a strong quadrupole component (WARWICK, 1966)) distorts the dipole field lines sufficiently to beam the emission towards the earth. Of these two possibilities, only L-shell crossing by particles or waves is likely. As we shall see below, the quadrupole component of Jupiter's field is almost certainly very small, inadequate to yield sufficient distortion.

ELLIS (1965) recently objected to the Cerenkov process on two grounds: (1) the emission may not be beamed along the lines of force, and (2) it may not escape the planetary atmosphere because of the stop band at $Y=1$ for emission generated at $Y>1$. The theoretical objection that the emission is not beamed along the field lines follows from an analysis (COHEN, 1961) of the Cerenkov process in a plasma without magnetic field. In that case only the plasma mode has an index of refraction greater than unity. When a field is present, however, the medium has a large index of refraction. MCKENZIE (1966) shows that in this case (with restriction on the magnetic field strength) emission concentrates along the field lines.

The relevance of the $Y=1$ stop band has been discussed elsewhere (WARWICK, 1963c; see also GULKIS and CARR, 1966). Many phenomena render escape of the extraordinary mode probable, and weaken an objection based on idealized plane waves propagating in a uniform medium. Some of these will be discussed in Section 10.3.

MARSHALL and LIBBY's (1967) proposed mechanism for DAM involves transitions between molecular spin states excited by hydromagnetic waves. The suggestion is motivated by laboratory measurements of 'spin-flip' radiation from free radicals.

In a solid state plasma, such a process occurs as a result of the transfer of energy from 'phonons', pressure waves in a crystal. The pressure wave description contains off-diagonal elements because of the crystalline lattice forces. Sound waves normally are purely longitudinal and cannot excite spin states of molecules. In the sense that off-diagonal terms appear in the pressure tensor for a plasma in magnetic field, it is analogous to a crystal. Hydromagnetic waves might induce spin transitions under the circumstances. The different free radicals that occur in Jupiter's atmosphere have slightly different properties, so that a number of frequencies near the electron gyro frequency will be excited simultaneously. Depending on the distribution of these radicals within the excited region, there may be radiation generated at a particular latitude, and therefore observed in a narrow frequency band. These are known to exist, an example is 4th source radiation (WARWICK, 1963a). The zenographic distribution of free radicals may be locally concentrated (as the distinct coloration and markings on Jupiter suggest), and could be responsible for other curious, repeating dynamic spectral details. In this mechanism the spatial coherence effects discussed earlier might result from a maser action following the simultaneous excitation of extensive regions by a hydromagnetic wave.

10. Magnetospheres of the Earth and Jupiter

10.1. RADIO EMISSION FROM THE EARTH

WARWICK (1963c) discussed terrestrial radio emission at decametric wavelengths. In the neighborhood of 700 kc/s, recent flights by rockets and satellites in the upper atmosphere indicate the presence of strong electromagnetic disturbances (HADDOCK *et al.*, 1964; HUGUENIN and PAPAGIANNIS, 1965; HARVEY, 1965; however, note also CALVERT and VANZANDT, 1966). This frequency lies close to the upper hybrid frequency, defined by $1-Y^2=X$. Further phenomenology is fragmentary. At the present time, we do not know whether the EM fields represent propagating waves, or, if they propagate, whether they escape into interplanetary space beyond the magnetosphere. Their relation to DAM is not clear, although there is a possible connection in that both are related to the magnetic field.

10.2. PARTICLES AND FIELDS IN THE MAGNETOSPHERE

This review is not the place for a comprehensive discussion of new information on the earth's radiation belts; please refer to COLE (1966).

10.3. NEUTRAL PLASMA WITHIN JUPITER'S MAGNETOSPHERE

ELLIS' (1965) theory depends crucially on the existence of dense neutral plasma far out in Jupiter's magnetosphere. There exists no deductive theory of the origin of this plasma. His emission mechanism therefore rests on an ad hoc assumption of the required plasma density.

To illustrate the importance of this question, note that WARWICK's (1963c) interpretation of the emission through the Cerenkov mechanism implies that the extraordinary mode somehow escapes the region of generation. Scattering on inhomogeneities may provide the route. However, as has long been recognized, in a smooth medium the radiation would have to cross a 'stop band' (ROBERTS, 1956), where the waves would be heavily absorbed. This stricture against the Cerenkov mechanism was invoked as a criticism of MARSHALL's (1956) theory of solar emissions. According to Warwick, the problem of radiation escape from the sun is, or may be, quite different from the problem of escape from a planetary atmosphere. In the solar atmosphere, dynamical phenomena make it likely that the magnetic field and plasma density become small together. In a planetary atmosphere, the scale height of the plasma is much smaller than the scale distance of the magnetic field. One might envisage a bounded plasma in a uniform field extending out into empty space.

Ellis disagrees with this point. He argues that above the earth's ionosphere the plasma extends many earth's radii into space. However, recent analyses (CARPENTER, 1966; ANGERAMI and CARPENTER, 1966) of whistlers at high geomagnetic latitudes show the existence of a 'plasma sphere' having electron densities of the order of 10^2 cm^{-3} and extending out to four earth's radii. Within this region, we assume that the plasma is given by a diffusive equilibrium model. Outside it, the plasma 'trough' is described by a collisionless model with a density of only a few electrons cm^{-3}. The reason for such a knee in the thermal plasma distribution may be the convective motion of the lines of force beyond it through the open magnetospheric tail (NISHIDA, 1966). Note that at the plasmapause a decrease in density by two orders of magnitude takes place within less than 0.15 earth's radii.

Theories of the magnetospheric thermal plasma consider the diffusive equilibrium of hydrogen and atomic oxygen up from the base of the magnetosphere where they are formed by photochemical processes. The relevant parameters are the particle thermal kinetic energy and the centripetal forces from the rotation of the planetary magnetic field. The latter can be estimated in terms of the ratio of the gravitational potential energy to the rotational energy, that is $\psi = GM_{\text{planet}}/\Omega^2 R^3$. $\psi \geqslant 1$ when $R \leqslant \sqrt[3]{GM_{\text{planet}}/\Omega^2} = 7\text{R}$ (earth), or 3.5 R (Jupiter). We estimate the importance of the thermal energy by the ratio $\phi = GM_{\text{planet}}m/kTR$, where m is the atomic or electronic mass, k is Boltzmann's constant, and T is the kinetic temperature of the particles with mass m. For temperatures of the order of 10^2 to 10^3 °K, protons have $\phi \lesssim 1$ everywhere above the earth. The centripetal force effects therefore become important on protons at distances greater than about 7 earth's radii or 3.5 Jupiter's radii, respectively for the two planets. For the electrons, centripetal forces are not important.

Within the earth's plasmasphere the density distribution therefore appears to be given by thermal diffusion (ANGERAMI and CARPENTER, 1966) for which the density decreases quite slowly outwards to the plasmapause at about 4 earth's radii. Beyond that point, the density falls off as R^{-4}, slightly more rapidly than the fall-off in magnetic field strength. Inside the plasmasphere the density is about 10^2 cm^{-3}, outside the plasmapause, the density is only a few cm^{-3}. There is very little theoretical basis on which to extrapolate the earth's plasmasphere to Jupiter.

The most direct evidence on the thermal plasma density in Jupiter's magnetosphere comes from the Faraday effect (WARWICK and DULK, 1964), which appears to exclude a plasma density greater than about 10 cm^{-3} at distances of the order of one radius from Jupiter. The observed lack of a Jupiter Faraday effect suggests that the radiation is produced in just one polarization mode near the surface of the planet. This mode, as it propagates through Jupiter's magnetosphere, must at some point move in a region where the observed elliptical polarization is not a characteristic mode, since the local magnetic field and electron density in Jupiter's magnetosphere are surely low enough that the modes are almost purely circular (as in the earth's ionosphere and magnetosphere). Yet we observe elliptical polarization. Therefore, mode coupling must occur somewhere between the source and the earth, at a point in Jupiter's magnetosphere. From the coupling region outward, the wave will be subject to Faraday rotation. But we observe little or no Faraday rotation attributable to Jupiter's magnetosphere. It is this situation that permits the above upper limit to be set on the plasma density near Jupiter, in its magnetosphere.

This density value disagrees violently with the values given by Ellis (1965), which are larger by three orders of magnitude at one Jupiter radius above the planet. Since the upper limit set by Faraday effect cannot be reconciled with Ellis' result, we must ask which density value, if either, is consistent with an extrapolation from the limited information available concerning the terrestrial magnetosphere. Suppose that Jupiter's source of thermal plasma is also upward diffusion of protons (produced by dissociation and photo-ionization from the molecular hydrogen that constitutes the bulk of Jupiter's atmosphere). For the earth, a critical height for the protonosphere is at 1500 km, where the density lies between 10^3 and 10^4 cm^{-3}. Below this height, protons undergo charge exchange with oxygen atoms and are lost. For Jupiter, we assume that protons are lost through charge exchange with hydrogen molecules at about the same absolute density value. The height at which this occurs is unknown for Jupiter, but I shall attempt to estimate it crudely.

The F-region temperature of the earth's ionosphere is about 1500°K. This temperature results basically from the high intensity of the solar trans-Lyman uv radiation which is responsible for Jupiter's ionosphere (Nicolet, 1960; Gross and Rasool, 1964). The rate at which this flux is absorbed and conducted away into the lower atmosphere determines its temperature. At 300 km in the earth's atmosphere, the flux impinges with full intensity and the temperature is about 1500°K. But by 100 km the radiation is fully absorbed and the temperature is a few hundred degrees.

We assume that the same absolute mass of gas produces the same relative absorption at Jupiter as at the earth. The solar flux is only $\frac{1}{25}$, and the acceleration of gravity is three times, the values for the earth. We assume that the mean molecular weight $\bar{\mu}=2$, and we estimate the temperature. If the heat conductivity K depends on T as $T^{\frac{5}{2}}$ for both Jupiter and the earth, we use the relation $\text{Flux}=K(\mathrm{d}T/\mathrm{d}h)$ and find

$$\frac{\text{Flux (Jupiter)}}{\text{Flux (earth)}}=\frac{1}{25}=\frac{\left(\dfrac{\mathrm{d}T}{\mathrm{d}h}\right)_{\text{Jupiter}}}{\left(\dfrac{\mathrm{d}T}{\mathrm{d}h}\right)_{\text{earth}}}\left(\frac{T_{\text{Jupiter}}}{T_{\text{earth}}}\right)^{\frac{5}{2}}$$

The density decreases about a factor of 2 in one scale height $kT/\bar{\mu}g$. We assume that T changes essentially within this same distance, for purposes of reckoning $\mathrm{d}T/\mathrm{d}h$ in the conducting region. That is, set $\mathrm{d}T/\mathrm{d}h = \bar{\mu}g/k$. Inserting this value in the previous flux relation, we find $T_{\text{Jupiter}} = 500\,°\mathrm{K}$. The corresponding scale height for the ionospheric molecular hydrogen is 84 km. This temperature is much hotter than the 140 °K found by Gross and Rasool (1964). The essential difference lies in the lower heat conductivity we assumed for Jupiter (the same value as for the earth).

Close to Jupiter's optical surface, there is a height where the total density compares with F-region densities in the earth's ionosphere, 10^{12} cm^{-3}. With the scale height just given, density of 10^3 to 10^4 cm^{-3} comes about 1700 km above the ionosphere. This height is only slightly greater than the corresponding height in the earth's exosphere, but is a much smaller fraction of a Jupiter radius, namely $\frac{1}{40}$ as compared with $\frac{1}{4}$. This difference is important inasmuch as the gravity of Jupiter remains essentially constant throughout the critical region of formation of the magnetospheric plasma, rather than decreasing significantly outwards as it does for the earth. We therefore believe that the plasmasphere of Jupiter will be confined to a significantly smaller region, and will have significantly lower densities than in the case of earth. The density will be perhaps 10 cm^{-3} as compared with 10^2 cm^{-3}, and since the earth's plasmasphere extends to about 25000 kilometers, we feel safe in concluding that Jupiter's plasmasphere lies well within one-third planetary radius. This figure is fully consistent with the observations of Faraday effect.

As Gross and Rasool (1964) emphasized, the small plasmaspheric densities and extent results from (1) the lower solar flux at Jupiter, (2) the small mass of the hydrogen molecule, the principal constituent of Jupiter's atmosphere, and (3) the greater gravity of Jupiter. These are all well-known quantities. The factors (1) and (3) surely decrease Jupiter's magnetospheric density, while (2) is essentially the same constituent that forms the earth's magnetosphere. While the above computation was radically over-simplified, a very small, close-in plasmasphere seems inescapable.

10.4. Satellite effects within Jupiter's magnetosphere

Io lies 6 radii from Jupiter's center. We take the density there from the density of the plasmasphere extrapolated by R^{-4}. The resulting values, 0.1 to 1 cm^{-3}, are very uncertain, but still above the interplanetary plasma density at Jupiter's orbit. If we extrapolate the dipole field determined by decametric observations, we find .05 gauss. The Alfvén speed at Io's orbit then is 10^{10} $\mathrm{cm}\cdot\mathrm{sec}^{-1}$. Io moves at about 2×10^6 $\mathrm{cm}\cdot\mathrm{sec}^{-1}$, very much less than the Alfvén speed. Relative to the plasma, which may co-rotate with Jupiter even at Io's position, the motion is 5.4×10^6 $\mathrm{cm}\cdot\mathrm{sec}^{-1}$.

This motion is so very much slower than the hydromagnetic speed that strong discontinuities, shock waves, seem unlikely. However, the presence of Io unquestionably generates a disturbance, analogous to the noise generated by wind flowing through tree branches. The strength of the noise, and the directional pattern in which it flows away from Io, depend on the detailed nature of the interaction. All wave polarizations and propagation directions are created as the magnetospheric plasma flows around the satellite. A wide band of frequencies will be generated, since the satellite is not a strongly resonant obstacle to the flow. In a rough sense, the characteristic frequency is given by the time taken for the magnetospheric gas to flow past Io: 3300 km/(54 km$\cdot$ sec^{-1})$=$61 seconds. Io represents such a large obstacle that higher frequency waves will be generated relatively weakly. We therefore consider only the three low-frequency hydromagnetic modes, the accelerated, retarded, and oblique Alfvén waves (DENISSE and DELCROIX, 1961).

This conclusion on the relevance of low frequency waves is opposite Ellis'. He believes (ELLIS, 1965) that Cerenkov radiation of high-frequency (essentially electromagnetic) modes may be important. In any case, the problem is to establish the boundary conditions at the moving satellite. If there is a strong discontinuity of the shock type, it must be of an electromagnetic variety, like Cerenkov radiation. Our present conclusion is that most of the disturbance energy created by the flow around Io lies at frequencies very low in comparison with EM frequencies characteristic of the magnetospheric plasma. Therefore, most of the disturbance energy is carried away as Alfvén waves.

The phase velocity of the oblique, accelerated, and retarded waves is $V_A \cos\theta$, V_A, and $V_{\text{sound}} \cos\theta$ respectively. They are non-dispersive waves, having identical group and phase velocities. For all directions of propagation, the fastest wave is the accelerated wave, for which electric and magnetic fields lie at right angles to the propagation direction. The oblique wave has an electric vector component along the propagation direction. Its magnetic vector is transverse. We assume that the Io disturbance may be represented by a superposition of these waves (see below for a discussion of the retarded mode).

The lines of force are essentially thrust aside as a result of Io's motion. A component of magnetic field in Jupiter's magnetic equatorial plane is created as a result. Either oblique or fast waves can be generated, although only the fast wave propagates in directions within the equatorial plane. The resonance condition permits an estimate of the total wave amplitude. Set the radius of curvature of the local disturbance on the line of force equal to R_{Io}. Then the preferentially generated waves will have an angular frequency of $\pi V_{Io}/R_{Io}$. We assume that the wave created by Io is sinusoidal, with spatial variation $B_0 + B \cos kz$; B_0 is the undisturbed magnetospheric field before Io arrives, B is the amplitude of the wave created by Io, k is the propagation constant of the wave, and z is distance along the line of force. Setting y=the coordinate at right angles to the direction of z, we find that the equation of the disturbed line of force is given by

$$y = \frac{B}{B_0} \frac{\sin kz}{k} + \text{constant}$$

The smallest radius of curvature along the line of force is given by

$$\left(\frac{d^2 y}{dz^2}\right)^{-1} = -\,B_0/(kB)$$

Then, let $R_{Io}=B_0/(kB)$. The angular frequency of the wave is $kV_{wave}=\pi V_{Io}/R_{Io}$ and therefore, $B=1/\pi \; B_0 \; V_{wave}/V_{Io}$. This expression for the wave amplitude exhibits the most important feature of the interaction, namely the very large amplitude that results from the large Alfvén-to-satellite speed ratio.

Since the magnetospheric plasma is compressible, the Alfvén waves may steepen into shocks (PARKER, 1960; BOLEY and FORMAN, 1964). However, our estimate of the disturbance field, *B*, is certainly too large. For example, if Io were a perfectly insulating body, it would not cause any effect at all. It seems likely, on the other hand, that Io is mildly conducting and will therefore tend to push aside the lines of force as we assumed in the above analysis (for a discussion of a similar problem in the case of our own moon, see GOLD, 1964). Boley and Forman use a first-order theory to predict the distance for steepening of an Alfvén wave into a shock; inclusion of the higher order terms needed to describe a large amplitude disturbance steepens the wave still faster. In the linear theory, the steepening distance is

$$s \sim \frac{2}{k} = \frac{2}{\pi} \frac{V_{wave}}{V_{Io}} R_{Io} .$$

This value is 15 times larger than the distance to the surface of Jupiter, but is probably much too large in view of the enormous amplitude of the disturbance wave at Io.

Io's velocity may be supersonic with respect to the retarded wave. The magnetospheric temperature of Jupiter is unknown. The ion energy would have to be less than 10 eV for the satellite to be supersonic with respect to this mode. The corresponding temperature is 10^5 °K. For corresponding regions of the earth's magnetosphere, the average particle energy is 350 eV (SAGALYN and SMIDDY, 1965). If Jupiter's magnetosphere has equally energetic particles, we need not consider the possibility of ion shock waves. It seems difficult to avoid the conclusion that the bulk of the energy flow resides in magnetohydrodynamic disturbances rather than sonic disturbances.

Other satellite effects may also be relevant; some of these will be listed here: J. D. G. Rather, and J. M. Witting (both works unpublished) have considered the satellite sweeping of trapped radiation. Such an effect in the earth's belts was considered by SINGER (1961). FIELD (1966) describes the Rather effect as creating a barrel-shaped moat in Jupiter's radiation belt. The two innermost satellites, Io, and Jupiter V ('Amalthea') determine where electrons precipitate. Rather compares Amalthea's redness with the moon's red fluorescence under solar particle bombardment (KOPAL and RACKHAM, 1963; SPINRAD, 1964; MIDDLEHURST, 1964; SUN and GONZALES, 1966). MOORE (1965) discusses the color of Io, its variability, and also the variability in brightness. RÖSCH (1966) published photographs of Io with darkening to the limb, and a narrow north–south surface marking. OWEN (1965) fails to find any non-solar spectral features on Io, and states that Jupiter's satellites have no atmosphere. This result contradicts observations by BINDER and CRUIKSHANK (1964).

A novel satellite observation was discussed by TIURI and KRAUS (1965), based on ionization effects connected with artificial satellites of the earth (TIURI, 1965). Observing with two-station radar, they detected disturbances of the electron density in the upper ionosphere. The satellite, they believe, triggers a disturbance which is visible at points along the magnetic shell it momentarily occupies. If we repeat the above analysis of Io's effect for satellites in the earth's close-in magnetosphere, we find that even small satellites produce a several-fold enhancement of the magnetic field. This Alfvén wave must steepen rapidly, within a few hundred meters of the satellite, into a shock whose further effects might create the disturbances observed by Tiuri and Kraus. This observation obviously is important, and should be confirmed independently.

10.5. JUPITER AURORAS

Whether Jupiter manifests auroras continues to attract attention. A new search (DULK and EDDY, 1966) failed to show any Hα emission at the equivalent of a 1.2 kilorayleigh terrestrial aurora. X-ray emission might be expected when the 10-keV electrons assumed to be involved in the decameter emission process penetrate Jupiter's atmosphere. FISHER *et al.* (1965) did not detect any one to ten angstrom bremsstrahlung emission at a level greater than 2.4×10^{-8} ergs$\cdot$cm$^{-2}\cdot$sec^{-1}. This lower limit is much higher than the anticipated flux.

To estimate the X-ray bremsstrahlung, we use formulas given by CHAMBERLAIN (1961). The total radiation is $(\Delta E)_{\mathrm{rad}} = 2E_0^2/1600$ MeV where E_0 = initial electron energy. With $E_0 = 10^{-2}$ MeV, $(\Delta E)_{\mathrm{rad}} = 10^{-7}$ MeV. This radiation goes into all directions. Assume that the source subtends 1.3×10^{-9} steradians (corresponding to an area extending across Jupiter's hemisphere, and $\frac{1}{5}$ of a radius along its meridian). At the earth, the X-ray flux is 10^{-16} MeV for each electron with energy E_0. Now assume an electron flux 4×10^{10} cm$^{-2}\cdot$sec^{-1} (WARWICK, 1963a). Then the X-ray flux at the earth is 4×10^{-12} ergs$\cdot$cm$^{-2}\cdot$sec^{-2}, in the spectral range near 10 Å. This flux is a factor of 10^4 less than that presently observable. However, even if it is this weak, the Jupiter source surely merits the flight of equipment with adequate sensitivity.

11. Conclusions

11.1. TYPES OF DATA THAT ARE NEEDED

For DIM, the problem of fixing the emission centroid remains, despite the very strong efforts by Roberts and Ekers, and by Berge. There are asymmetries in DIM and DAM, whose only explanation has been in terms of the displaced dipole. A satisfactory answer may depend on studies carried out in real time by a second-of-arc pencil beam. One might discern the thermal emission from Jupiter's disk embedded in the halo of radiation belt emission. The observations then would be self-calibrating. Such a measurement would require apparatus with multiple-pencil beams of the order of 5 seconds of arc. There might also be discernible local effects of Io and Amalthea on DIM (Rather, unpublished).

More immediate problems for DIM certainly include refinement of the rotational period, in view of its apparent disagreement with DAM's rotation period. BARBER (1966) and DICKEL (1967) believe that the period lies within 0.2 seconds of the system

III (1957.0) period. Periodic checks of the rotational period seem important, and can be carried out with relatively simple equipment.

Many stations around the world now observe DAM, although the concentration is heaviest in the U.S.A. There is value in 24-hour synoptic coverage at limited frequencies (ALEXANDER, 1966). Such a study might possibly have suggested Io's modulation earlier, had it been available. The current tendency for observers of DAM to publish their data in summary form is also much to be recommended (see, for example, the catalogue of MORROW, BARROW, and RESCH, 1965).

However, the principal information needed is more refined data, especially on the fast-time resolution polarimetry and spectroscopy of millisecond bursts. The polarization diversity on these bursts as recorded at Arecibo needs confirmation. At Boulder equipment is being set up for continuing the study, but it may suffer from lack of antenna collecting area. In addition we plan to extend the swept-frequency receiver towards higher frequencies, from 40 to 80 Mc/s. Continuous coverage of that range, with high sensitivity, is required to establish the existence of possible localized spectral islands of emission. These would have escaped detection in any DAM surveys made to date. The ionospheric Faraday effect on Jupiter bursts should be observed with higher precision than so far accomplished. One possible result of such a study might be the detection of the effects of Jupiter's rotation in the orientation of DAM's polarization ellipse.

Radar observations of Jupiter promise much for the future. The detection of echoes from this soft target is apparently variable (PETTENGILL, 1965). PETTENGILL (1966) also notes that improving radar system power may permit detection of echoes from Jupiter's Galilean satellites in the next decade, and suggests that the polarization should be measured as the satellite is occulted by Jupiter's ionosphere. Such measurements could provide an independent determination of Jupiter's magnetic field.

11.2. SPACE OBSERVATIONS

If, as is likely the case, DAM is generated near the electron gyro frequency of Jupiter's ionosphere and magnetosphere, a lower limit of the emitted frequency is given by the weakest field containing emitting particles or waves. These fields lie at the outermost parts of the magnetosphere of Jupiter, whose extent is uncertain (say, 10–50 Jupiter radii; in the magnetospheric tail, the distance is still greater; this structure undoubtedly subtends degrees in our sky!). At the magnetopause, the gyro frequency is about 100 cps, and at Io, 150 kc/s. The interplanetary plasma frequency corresponding to one electron cm^{-3} is 9 kc/s. Observations of the lower limit of radio emission from Jupiter may succeed if sensitive radio telescopes are placed outside of the earth's magnetosphere.

11.3. OBSERVATIONS OF JUPITER'S RADIATION BELTS

All known facts concerning non-thermal phenomena at Jupiter derive from radio astronomical data. *In situ* verification of the inferred particles and fields seems to most radioastronomers to be a priority item for space research. To design and fly apparatus to Jupiter is not easy. The equipment must survive not only a long voyage, several years in length, but also an obviously hostile environment upon its arrival. Benefits that might accrue to such a flight are:

(1) deeper understanding of plasma physical processes of generation and acceleration of energetic particles;

(2) understanding of non-linear mechanisms for creation of radio emission from plasmas;

(3) understanding of the origin of magnetic fields in rotating bodies;

(4) observations of the solar wind and energetic particles at radically different places within the solar system.

Objectives such as these justified space probes within the inner planetary system. A Jupiter probe, and especially a Jupiter orbiter, enhances the prospects of a pay-off, because this planet, uniquely aside from the earth, is known to involve the phenomena of interest.

11.4. ASYMMETRIES IN JUPITER'S MAGNETIC FIELD

There remains an outstanding inconsistency in the data on the symmetry of Jupiter's magnetic field. Everyone agrees that DAM requires departure of the planetary field from a centered dipole. I find it necessary to review my reasons for suspecting that the nature of these departures is not resolved at present, despite the wonderful measurements by Roberts and Ekers. If the centroid of DIM is at the mass center, the evident asymmetry of the direction of DIM's polarization as function of longitude requires explanation, as does the variation of intensity, as a function of zenomagnetic latitude of the earth. At present, no explanation other than planetary shadowing of southward-shifted radiation belts has been advanced for the polarization effect. It now appears (Section 3.2) that the intensity effect shows that Jupiter's magnetic field is a very pure dipole. The suggestion that distortion of the dipole field produces the polarization effect therefore cannot be supported.

In Section 3.2 we showed that ROBERTS and KOMESAROFF's (1965) determination of intensity as a function of latitude is symmetric around zenomagnetic latitude +1.2°. This latitude represents the effective magnetic equator of Jupiter, so far as the mirroring of the relativistic electrons is concerned. Assume that the observed asymmetry derives from a magnetic field made up of an axi-symmetric quadrupole field added to the pre-existing dipole field. The mirror-point equator (where the minimum magnetic field exists) lies north of the dipole equator. To achieve this, the southern pole of Jupiter's magnetic axis must have a stronger field (in agreement with the displaced dipole model for DAM). If the magnetic field is made up of an axi-symmetric quadrupole field added to a dipole field, the quadrupole has negative poles (with inwardly directed field lines) and a positive center (with outwardly directed fieldlines).

Detailed calculations show that for synchrotron emission at 2.5 radii from the center of Jupiter, the required asymmetry is achieved if the ratio of quadrupole to dipole moment is .018 in units of Jupiter's radius. If both the dipole and the quadrupole lie at Jupiter's center, the ratio of equatorial field strengths is .0552. The southern polar field is slightly stronger than the northern, but the difference is too small to account for the asymmetries of DAM or the polarization asymmetry of DIM. The quadrupole field of the earth is .08 that of the dipole, and the earth has rather strong higher pole components as well. In other words, it seems that Jupiter's field is a more purely dipole field than is the earth's field.

In the quadrupole model, there is a difference between the zenomagnetic latitudes in the northern and southern hemispheres where the line of force through Io intersects the surface of Jupiter. However, this difference amounts to only about four degrees, again emphasizing the purity of Jupiter's dipole field.

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