THE MAGNETOSPHERE OF JUPITER

By Thomas D. Carr[1]
Department of Physics and Astronomy, University of Florida
Gainesville, Florida

and Samuel Gulkis[2]
Jet Propulsion Laboratory, Pasadena, California

INTRODUCTION

The only solar system objects known to possess magnetic fields are the Earth, the Sun, and Jupiter. The field of the Earth can be measured directly, while that of the Sun has been deduced from the observed Zeemann splitting of optical emission lines. The first evidence that Jupiter has a magnetic field, and thus far the only evidence, was provided by its polarized radio emissions. Jupiter's field is believed to be considerably stronger than that of the Earth. As in the case of the Earth, Jupiter's field does not extend indefinitely into space, but is confined to a cavity of unknown size and shape around the planet. Outside this cavity and beyond a transition region, the ambient conditions are characteristic of the interplanetary medium. The region within the cavity, in the space above the ionosphere, is termed the magnetosphere. Inside the magnetosphere, the magnetic field has control over the fast charged particles responsible for much of the Jovian microwave emission, and presumably also a background plasma with a broad spectrum of particle energies extending down into the thermal region. Because of the relatively high rotation rate of the planet, its strong magnetic field, and the presence of a number of satellites orbiting within its magnetosphere, magnetic interactions are believed to play an even more important role in Jupiter's magnetosphere than in that of the Earth. In this paper we shall discuss the observed radio emissions, the deductions from them regarding the magnetic field and the magnetosphere, and the results of theoretical investigations of interactions between the magnetic field and plasma in the Jovian magnetosphere.

NONTHERMAL DECIMETRIC RADIO EMISSION

Although the discovery of the Jovian decametric emission (Burke & Franklin 1955) antedated that of the decimetric component, we shall discuss

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the latter first because it is better understood. Following the discovery of thermal emission from Jupiter at 9540 MHz (Mayer et al. 1958), Sloanaker (1959) observed a nonthermal component at 3000 MHz. Subsequent measurements by several groups established the nonthermal character of this radiation in the frequency range between 400 and 3000 MHz. Drake & Hvatum (1959), Roberts & Stanley (1959), Field (1959, 1960, 1961), Radhakrishnan & Roberts (1960), Morris & Berge (1962), Chang (1962), Chang & Davis (1962), McClain et al. (1962), and Gary (1963) laid the foundations for the well-established theory of Jupiter's synchrotron emission, which is most pronounced at decimeter wavelengths. Distinguishing characteristics of this radiation component are its nonthermal spectrum, the relatively large extent and distinctive shape of the emitting region, the relatively high degree of linear polarization, the very small degree of circular polarization, and the beaming effect. These are all attributes of synchrotron emission by high-energy electrons trapped in a dipole magnetic field (Ginzburg & Syrovatskii 1965), and there can be little doubt that the synchrotron emission mechanism is responsible. Although the existence of a Jovian magnetic field was originally inferred from observations of circularly polarized decametric radiation, the first conclusive proof was provided by the observations of synchrotron radiation. Good reviews of the state of research on the decimetric component through 1965 or 1966 have been published by Roberts & Komesaroff (1965), Roberts (1965), and Warwick (1967).

Spectrum at meter, decimeter, and centimeter wavelengths.—The extreme high-frequency end of Jupiter's radio spectrum is dominated by thermal emission, as can be seen from Figure 1. The observed points above 5000 MHz lie close to the spectral curve calculated on the assumption that Jupiter's disc is an ideal blackbody radiator at 130° K, the measured infrared temperature (Menzel et al. 1926). Roberts (1965) concluded that over the decimetric range the spectrum is almost flat, the average flux density being 6.7 ± 1.0 1 f.u. (1 f.u. $= 10^{-26}$ Wm^{-2} Hz^{-1}) at the standard distance of 4.04 a.u. Barber & Gower (1965) have determined the mean spectral index between 178 and 610 MHz to be -0.21 ± 0.16. No radiation from Jupiter has yet been observed between 178 MHz and the high-frequency cutoff of the decametric spectrum at ~40 MHz. Detection of an extension of the decimetric spectrum into this region is particularly difficult because confusion effects due to the background are much greater here than at higher frequencies. The nonthermal component of the decimetric radiation may also decrease rapidly above 2700 MHz, as will be shown later. Although the thermal emission from the disk is insignificant at frequencies below 1000 MHz, it is at least as intense as the nonthermal component at 5000 MHz.

Stability of the decimetric spectrum.—The earlier decimetric measurements indicated irregular fluctuations in flux density occurring over periods of months, weeks, and even days (McClain et al. 1962, Drake & Hvatum 1959, Sloanaker & Boland 1960, Huguenin & Roberts 1962, Roberts 1962, Miller & Gary 1962, and Gary 1963). Roberts' (1962) observations suggested

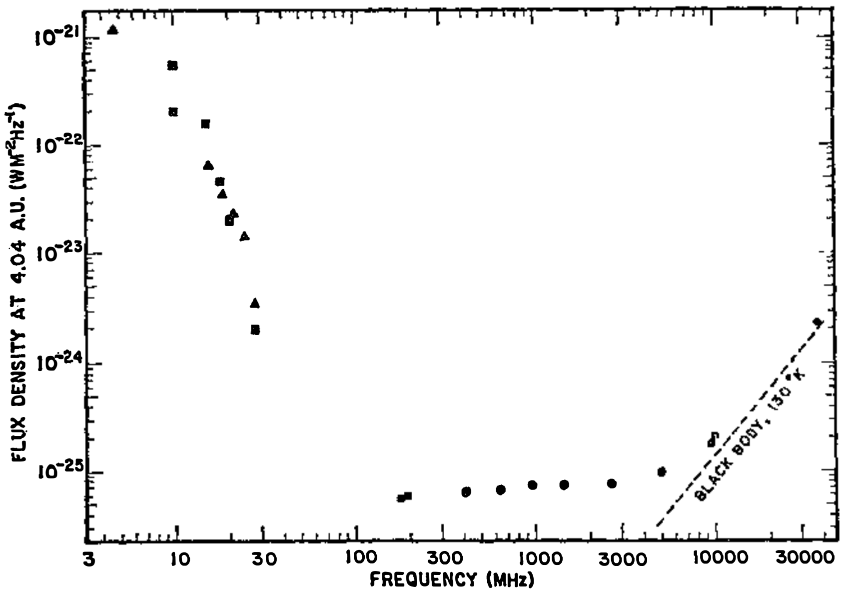

FIG. 1. Average power spectrum of the radio emission from Jupiter. Square points are from Carr et al. (1964), triangles from McCulloch & Ellis (1966), and circles from various sources, as quoted by Roberts (1965).

that the linearly polarized component is responsible for most of the variation. Some of the fluctuations were believed to be related to changes in the intensity of the solar wind. More recently, Bash et al. (1964), Roberts & Komesaroff (1965), Davies & Williams (1966), Miller & Griffin (1966), Berge (1966), Tiberi (1966), and Rose (1967) have concluded that the apparent irregular variations were largely or entirely due to background confusion effects. However, as several authors have pointed out, most of the precise intensity measurements reported were made during years of minimum solar activity, so that the possibility of large changes during solar maximum cannot yet be ruled out. Moreover, slight changes in intensity occurring over intervals of several years are considerably more likely.

Longitude variation of total intensity.—The variation of the total intensity ("intensity" and "flux density" are used interchangeably) of the decimetric radiation with the System III (1957.0) longitude of the central meridian (CML) is shown in Figure 2b (Roberts & Komesaroff 1965). This effect is attributed to the beaming of radiation in the equatorial plane of a slightly tilted dipolar magnetic field (Morris & Berge 1962, Gary 1963, Bash et al. 1964, Roberts & Komesaroff 1964). Synchrotron radiation by ultrarelativistic electrons describing relatively flat helical orbits (i.e. with pitch angles close to 90°) is emitted most strongly in directions which are nearly per-

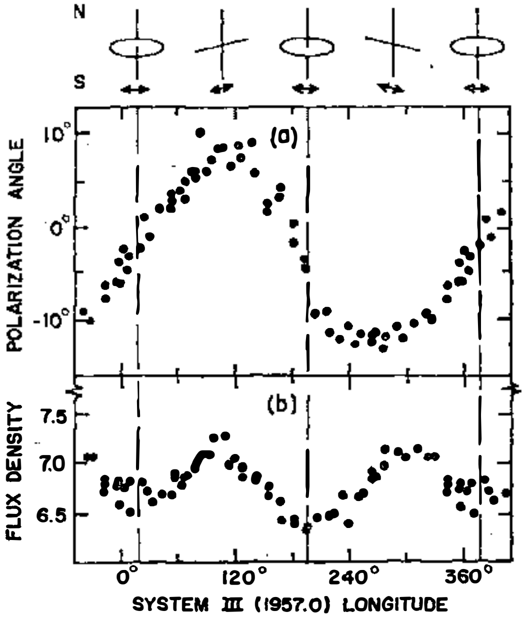

FIG. 2. (*a*) Angle of polarization with respect to the plane of the rotational equator, presented as a function of CML. (*b*) Equivalent flux density at 4.04 a.u. as a function of CML. Observations were made at 1430 MHz in Aug. 1963. (From Roberts & Komesaroff 1964.) The rotating disc at the top suggests the relative orientation of the plane of the magnetic equator at successive values of CML; arrows suggest polarization directions. CML values of magnetic poles are indicated by vertical dashed lines.

pendicular to the magnetic field. Assuming a dipole field with its axis slightly inclined to the rotational axis, beaming would thus occur in the plane of the magnetic equator (i.e. the symmetry plane of the field). The intensity of the radiation reaching the Earth would undergo a maximum twice each rotation, whenever the magnetic equator is viewed on edge. The two minima would occur when the two magnetic poles are tipped directly toward and away from the Earth, respectively, since the Earth lies within $\pm 3°$ of the plane of Jupiter's rotational equator (i.e. the plane perpendicular to the rotational axis). The System III (1957.0) longitudes toward which the poles were tipped in 1963 and 1964 were about 18° and 198°, as indicated by the vertical dashed lines in Figure 2. The beaming can be represented to a first approximation by

$$S = S_0 \cos^n \Phi_m \qquad 1.$$

where S is the observed total flux density, Φ_m is the Jovicentric magnetic latitude of the Earth at the time of observation (i.e. the direction angle of the Earth northward or southward from the magnetic equator), and n is an exponent to be adjusted to fit the data. The magnetic latitude is given by

$$\sin \Phi_m = \cos \beta \sin D_E + \sin \beta \cos D_E \cos (\lambda_{III} - \lambda_0) \qquad 2.$$

where β is the angle of tilt of the dipole axis relative to the rotational axis, D_E is the Jovicentric declination of the Earth, λ_{III} is the CML at the time of observation, and λ_0 is the CML when the magnetic pole in the northern hemisphere is tipped directly toward the Earth.

The variation of the total flux density with the rotation of Jupiter is most apparent at frequencies between about 1000 and 5000 MHz. Roberts & Komesaroff (1965) failed to observe the effect at 408 MHz, although it was found to be present to some extent at 430 MHz by Tiberi (1966) and at 620 MHz by Roberts & Ekers (1968).

Degree of polarization.—The linearly polarized component is much stronger than the circularly polarized component, which is almost below the limit of detection. The value of m, the degree of polarization, is $\sim$0.22 from 300 to 2800 MHz. Several observers have found a slight variation in m with central meridian longitude. This is to be expected, since the theory indicates that for synchrotron radiation from electrons in relatively flat helical orbits, the value of m should be highest approximately in the plane of maximum beaming (Roberts & Komesaroff 1965).

Synchrotron emission spectrum.—The polarized component decreases rapidly in intensity above 2800 MHz, but it is not clear whether this decrease is due to a decrease in the total intensity of the nonthermal component, or to a decrease in the degree of polarization of this component. Both Dickel (1967) and Morris et al. (1968) found that the flux density of the nonthermal component at 4995 MHz is $\sim$4 f.u. (i.e. only about 60 per cent of the value occurring over most of the decimetric range), provided the degree of polarization for the nonthermal component alone is assumed to be 0.22 at this frequency. However, an unambiguous determination of the shape of the nonthermal spectrum at the higher frequencies must await more accurate assessments of the relative proportions of the thermal and nonthermal components. Higher-resolution measurements are required to distinguish the radiation belt emission from that of the disk at centimeter wavelengths, and to reduce the background confusion at meter wavelengths.

Rocking of the polarization plane.—As discovered by Morris & Berge (1962) and illustrated in Figure 2a by the data of Roberts & Komesaroff (1965), the polarization plane rocks back and forth $\pm 10°$ relative to the rotational equator as the planet rotates. Since most of the radiating electrons mirror within about a planetary radius of the magnetic equator, the observed polarization plane must be nearly perpendicular to the magnetic field there (Davis & Chang 1961). Thus the $\pm 10°$ rocking of the polarization plane indicates that the magnetic equator is inclined $\pm 10°$ with respect to the rotational equator. One or the other of the magnetic poles must lie on the central meridian whenever the electric vector of the polarized component is perpendicular to the axis of rotation, if the field is assumed to be a dipole field. It can easily be deduced which of two central meridian longitudes corresponds to the pole in the northern hemisphere (see top of Figure 2).

Field asymmetry.—If the field were that of a perfect dipole, Figure 2a should be very nearly sinusoidal, and the CML values for zero polarization angle in Figure 2a should coincide with those of the flux-density minima in Figure 2b. An appreciable departure from these conditions is apparent from the figures, leading to the conclusion that there is a substantial distortion from the pure dipole field configuration. Two methods have been used in estimating β and λ_0, giving somewhat different results. In some cases, β has been assumed to be the amplitude of the fundamental component of the Fourier expansion of the position angle of the polarization direction measured as a function of CML, and λ_0 the value of CML at the downward zero crossing of the polarization angle for the fundamental component. In this way Roberts & Komesaroff (1965) found that $\beta = 10\overset{\circ}{.}0 \pm 0\overset{\circ}{.}3$ and $\lambda_0 = 189° \pm 4°$. In other cases, β and λ_0 were deduced from the variation of total intensity with CML. For example, Roberts & Ekers (1968) found the best fit of Equations 1 and 2 to their data, letting β, n, S_0, and λ_0 be the adjustable parameters.

The shape of the curve of flux density vs. CML (Figure 2b) will depend on both the Jovicentric declination of the Earth (D_E) and the effect of field distortion. For a perfect dipole field, the flux density should be a function only of the magnetic latitude of the Earth (Φ_m) as Jupiter rotates. Flux densities at corresponding north and south magnetic latitudes should then be equal. Actually, Roberts & Komesaroff (1965) and Roberts & Ekers (1968) observed that in general they are different. For example, Roberts & Ekers found at 2650 MHz that when β is assumed to be 10°, the value of n in Equation 1 is 6.9 for the points of negative Φ_m alone, while n is 3.6 for positive Φ_m points. On the other hand, it was discovered that if a single value of n is used, and if β, n, S_0, and λ_0 are all adjusted to yield the best fit to all the data points, the values obtained are $\beta = 15\overset{\circ}{.}7$, $\lambda_0 = 198° \pm 5°$, $n = 1.7$, and $S_0 = 7.60 \pm 0.02$ f.u. Other observers have also deduced values of β significantly higher than 10° from observations of flux density as a function of CML (e.g. Bash et al. 1964, Barber 1966). However, Warwick (1967) noted that if the flux-density measurements of Roberts & Ekers are plotted against Φ_m', where $\Phi_m' = |\Phi_m - 1\overset{\circ}{.}2|$, and β is assumed to be 10°, a single curve of the form $\cos^4 \Phi_m'$ fits the points well. This suggests that the beaming is maximum in directions lying $1\overset{\circ}{.}2$ northward from the plane of the magnetic equator. Warwick attributes this distortion to a magnetic quadrupole so arranged that the field at the principal pole in the northern hemisphere is slightly weaker than that in the southern hemisphere. Warwick's suggestion merits further study.

Source size and shape.—From interferometric observations at 2880 and 1415 MHz, Berge (1966) was able to construct a two-dimensional contour

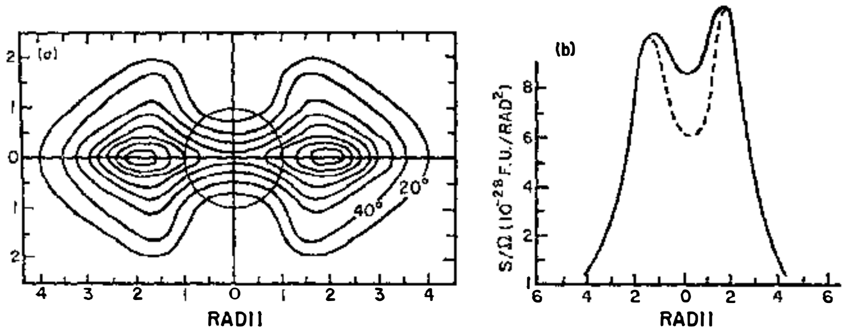

FIG. 3. (*a*) Brightness temperature model of Berge (1966). The contour interval is 20° K; CML (System III) is 20°. (*b*) Equatorial strip-brightness distribution measured by Branson (1968); dashed line indicates residue after removal of 250° K disc component.

map of the brightness temperature of the emitting region. Although his observations were not sufficiently detailed to yield an unambiguous plot, he was able to find a model which fit the data. The assumptions were made that the synchrotron emission component is distributed symmetrically with respect to the axis and equator of a roughly dipolar magnetic field, that the field axis is tilted an undetermined amount with respect to the rotational axis, and that a thermal-emission component of undetermined brightness temperature is uniformly distributed across the planetary disc. The model which fit the 2880 MHz observations best is shown in Figure 3a. The brightness temperature peaks occur on the magnetic equator at ~2 disc radii on either side of the center. A rather surprising result of Berge's study is that the disc temperature for the thermal component at 2880 MHz appears to be ~260° K, twice the temperature inferred from infrared and higher-frequency microwave measurements. One possible explanation is based on an earlier suggestion by Field (1959) that because of the presence of ammonia, lower frequencies in this portion of the thermal spectrum may arise from lower regions of Jupiter's atmosphere, where the temperature is higher. The model deduced from 1415 MHz observations differed from the 2880 MHz one only in minor respects. Note that brightness distributions, such as those of Figure 3, do not depict a true projection of the Jovian Van Allen belt because of beaming and related effects.

Roberts & Komesaroff (1965) concluded from partially successful observations of a lunar occultation of Jupiter that the source size does not change greatly between 408 and 1430 MHz. However, scans across the emitting region made at 408 MHz by McAdam (1966), using a radio telescope with a beamwidth comparable to the source width, could be interpreted as suggesting the presence of both inner and outer belts. The postulated inner belt would correspond roughly to that found by other observers, while the outer one, which would be considerably weaker, appeared to extend ~3 times as far.

Branson (1968), using the Cambridge 1-mile radio telescope, obtained contour maps of the emitting regions at 1430 MHz by an aperture-synthesis process. A map was obtained at each of three values of CML spaced 120° apart. They illustrate strikingly the large extent of the synchrotron emitting region, the tilt of the magnetic equatorial plane, and a definite asymmetry in the emitting region. Figure 3b shows the integrated-vertical-strip brightness distribution along the equator, at a time when the CML was 255° and Φ_m nearly zero. There appears to be an anomaly in the electron density, or more probably in the magnetic field, at a System III longitude of about 190°, leading to a slight excess of radiation from this region. The thermal disc temperature was found to be 250° K, in agreement with Berge's value. Branson also found that the brightness distribution at 400 MHz was almost the same as at the higher frequency.

Gulkis (1969) observed a lunar occultation of Jupiter at 405 and 234 MHz. His preliminary results confirmed the presence of the asymmetry reported by Branson. The ratio of the integrated flux from the east half to that from the west half was about 1.2. This is substantially in agreement with Figure 3b, for which the CML was approximately the same as during the occultation.

In an early theory by Warwick (1963b) accounting for some of the observed decametric phenomena, the magnetic field was assumed to be due to a dipole which is displaced as much as 0.7 radius from the center of the planet. However, Roberts & Ekers (1966) showed that the centroid of the emission at 2650 MHz coincided with the ephemeris position of Jupiter to within ± 0.1 radius in right ascension and to within ± 0.3 radius in declination. Branson (1968) arrived at a similar conclusion.

Circularly polarized component.—Berge (1965) succeded in measuring the circularly polarized component of the emission, which is very weak. The region of right-hand circular polarization was centered at λ_{III} (1957.0) $\approx 340°$, and that of left-hand polarization at λ_{III} (1957.0) $\approx 160°$. The maximum degree of circular polarization was roughly 0.03. Berge does not rule out the alternative possibility that he was observing the effect of an eccentricity in the centroid of emission rather than a circularly polarized component. However, he does not consider this likely.

Lack of influence by Io.—The discovery of the striking effect of the orbital position of Jupiter's satellite Io upon the decametric emission, to be discussed later, stimulated a search for Io-related effects on the decimetric radiation. None has been found (Dickel 1965, Barber 1966, Tiberi 1966).

Decimetric rotation period.—The System III (1957.0) rotation period was defined on the basis of the early decametric observations. Mean rotation period measurements can also be made at decimeter wavelengths by comparing the longitude distribution of either polarization angle or total intensity with a similar distribution obtained several years later. The most reliable measurement to date is apparently that of Komesaroff & McCulloch (1967). It was deduced from longitude distributions of polarization angle obtained in 1963 and in 1967. The indicated rotation period was $9^h\ 55^m\ 29^s.83 \pm 0^s.26$, or about $0^s.46$ longer than the System III (1957) period. No indication of any change with time has yet been found.

Further theoretical interpretations.—The general theory of synchrotron emission has been known for many years (see, for example, Jackson 1962, Ginzburg & Syrovatskii 1965), although there have recently been significant modifications to the theory (Epstein & Feldman 1967). One-dimensional or integrated distributions of the intensity and polarization of the synchrotron radiation from ultrarelativistic electrons trapped in a distant dipole field have been computed by Chang & Davis (1962), Field (1961), Huguenin & Roberts (1962), Korchak (1963), and Thorne (1965). Ortwein et al. (1966) have extended this work by calculating two-dimensional distributions of the Stokes parameters. Before commenting further on these detailed theoretical investigations, it is worthwhile to consider the spectrum of the radiation from a single ultrarelativistic electron moving in a magnetic field, and to make some elementary calculations based on synchrotron emission formulas. These considerations are useful in determining order-of-magnitude estimates of the field strengths and electron energies involved, and illuminate the intimate relationships between these quantities which make the interpretation of the observational data in terms of a unique model exceedingly difficult. A single electron of energy E radiates synchrotron emission with an intensity spectrum which exhibits a $\nu^{1/3}$ increase up to a critical frequency, and decreases exponentially at higher frequencies. Ginzburg & Syrovatskii show that the maximum in the spectrum occurs at a frequency ν_m, which is proportional to HE^2, while the power radiated per unit frequency interval at ν_m, $p(\nu_m)$, is proportional to H. The exact relationships are given by Equations 2.23 and 2.24 of Ginzburg & Syrovatskii.

Although the observed Jovian spectrum is nearly flat over a wide range of frequencies, there is some indication of a broad maximum at $\sim$850 MHz (Barber 1966). Substituting this value of frequency into Equation 2.23 of Ginzburg & Syrovatskii, we obtain $HE^2 \approx 1.8 \times 10^{14}$ G (eV)^2 or 4.7×10^{-10} G erg^2. Barber & Gower (1965) and Dickel (1967) have obtained similar values. It is generally true that measurements of the frequencies of emission do not lead to unique values of either H or E, but rather a combination of the two. Thus, if H in the radiation belt is 1 G, the electron energy must be $\sim$14 MeV to produce the observed maximum. The maximum could be produced by weaker or stronger field strengths by adjusting the electron energy accordingly. If it is assumed that the flux density observed at the Earth at the frequency ν_m originates from those electrons whose spectrum peaks near this frequency, the expression for the observed flux density can be written as $p(\nu_m)\ N_e/4\pi R^2$, where N_e is the total number of radiating electrons, and R

the distance. Substituting the observed value of flux density (7.3 f.u.) we obtain $HN_e = 1.5 \times 10^{28}$ G. This is essentially the same value obtained by Barber & Gower (1965). If H is assumed to be 1 G, N_e is $\sim 10^{28}$.

Considerations based on containment and time scales can also be used to put limits on H, E, and the density of radiating electrons (n_e). If we assume the volume of the radiating region to be roughly that between two coaxial cylinders of diameters 3 and 1 planetary diam, respectively, and each of altitude equal to 1 planetary diam, then n_e is $\sim 10^{-3}$ cm^{-3}. The energy density for the 14 MeV electrons would be n_eE, or $\sim 10^{-8}$ erg cm^{-3}. The magnetic energy density for a field of 1 G would be $\sim 4 \times 10^{-2}$ erg/cm^3, which greatly exceeds the relativistic electron energy density. The condition assumed in the derivation of the synchrotron emission formulas, i.e., that the magnetic field exerts control of the motion of the electrons, is thus satisfied.

The time T_M required for an ultrarelativistic electron to radiate half its initial energy is proportional to $H^{-3/2}\nu_m^{-1/2}$, as given in Equation 5.45 of Ginzburg & Syrovatskii. With ν_m taken to be ~ 850 MHz and $H \sim 1$ G, T_M is found to be ~ 0.7 year. Whatever the source of power for the Jovian synchrotron radiation, one would not expect to observe significant fluctuations in its intensity having periods much shorter than T_M. Komesaroff & McCulloch (1967) reported values obtained by themselves and others under comparable conditions at ~ 2700 MHz as 7.50 ± 0.1 f.u. in 1963, 7.60 ± 0.1 f.u. in 1964, and 7.30 ± 0.1 f.u. in 1967. This lack of a significant variation in flux density over a 3.2 year period might be attributed to (*a*) a value of H less than ~ 0.3 G, giving a value of T_M larger than 3 years, or (*b*) some other source of power than the solar wind. It is obviously very important that the Jovian decimetric radiation be monitored in a consistent manner over a full solar cycle.

Thorne (1965) computed the energy and pitch-angle distributions for a thin shell of synchrotron-emitting electrons crossing the equator at 3 planetary radii, the field being that of a centered dipole with its axis inclined 10° with respect to the rotational axis. The distributions were adjusted to yield radiation parameters which were based largely on the observations of Roberts & Komesaroff (1965), but without the observed asymmetries with respect to the magnetic equator. The indicated numbers of electrons per cm^3 with energies between E and $E+dE$ and with pitch angles between α and $\alpha+d\alpha$ were proportional to $(\sin^3 \alpha)E^{-1}$ at 408 MHz, and to $(\sin^2 \alpha + 2 \sin^{40} \alpha)E^{-1}$ at 1430 MHz, respectively. The E values ranged from $1.4H_0^{-1/2}$ to $140H_0^{-1/2}$, H_0 being the equatorial magnetic-field strength in gauss. Although Thorne's approach is instructive, his results cannot be very realistic. In the first place, it was assumed that there is no beaming at 408 MHz, while the results of Tiberi (1966) indicate that there probably is. A more fundamental difficulty is that a thin-shell model cannot be made to represent a true brightness distribution which is actually quite thick, as Berge (1966) has pointed out. Thorne showed that the observed flat radiation spectrum could be a consequence of a $1/E$ electron energy distribution. Roberts &

Komesaroff (1965) suggested that electrons are continuously being injected into the radiation belt at the highest energy, but that radiation losses reduce the energy in such a way that the $1/E$ distribution is maintained.

The two-dimensional distributions of Stokes parameters which have been calculated by Ortwein et al. (1966) should make possible the development of more realistic models. Berge (1966) suggested that a thick-shell model which accurately fits the observed brightness distribution might be built up by the superposition of a series of properly selected thin-shell models crossing the equator at various distances.

Roberts & Komesaroff (1965) have shown how H in the radiation belt can in principle be deduced from a measurement of the degree of circular polarization. At a frequency ν (in MHz) which is near the frequency of maximum synchrotron emission, the degree of circular polarization m_c is given approximately by

$$m_c = 0.72(H\nu^{-1} \sin \theta)^{1/2} N'(\theta)/N(\theta) \qquad 3.$$

where θ is the angle between the propagation direction and the magnetic field, $N(\theta)$ is the electron pitch-angle distribution $N(\alpha)$ evaluated at $\alpha=\theta$, $N'(\theta)$ is the derivative of $N(\alpha)$ evaluated at $\alpha=\theta$, and H is the magnetic-field strength (in gauss) in the belt. Berge (1965) used this expression to calculate H from his measured value of m_c. Since $N(\alpha)$ and $N'(\alpha)$ are not yet known with any certainty, Berge made a guess of 4 for the value of $N'(\theta)/N(\theta)$. Assuming that $m_c=0.1$, he obtained the value $H \approx 1$ G. On the other hand, if $m_c=0.01$, then $H_0 \simeq 0.1$ G. The uncertainties are quite large, but the method is interesting. It is the only known method by which H might be determined directly from measurements of the synchrotron radiation. Unfortunately, it does not appear possible to measure m_c with the required accuracy.

Legg & Westfold (1968) have recently verified the general conclusions reached by Roberts & Komesaroff regarding the circularly polarized component, but they showed that additional terms should be included in Equation 3. Thus, for an isotropic pitch-angle distribution, Equation 3 overestimates H for a given m_c by a factor of 9.

Berge was also able to deduce the direction of the magnetic field from his measurements of circular polarization. When the pole in the northern hemisphere was tipped toward the Earth ($\lambda_{III} \simeq 200°$), the circularly polarized component was in the left-hand sense. At this time the emitting electrons, which orbit almost in the plane of the magnetic equator, appeared from the Earth to be moving clockwise. Therefore the direction of the field at the equator must be southward. Field lines emerge from the pole in Jupiter's northern hemisphere, and converge toward the one in the southern hemisphere. Although the magnetic moment and angular momentum vectors are antiparallel in the case of the Earth, they are parallel on Jupiter. This is in agreement with results previously inferred for the decametric radiation (Dowden 1963, Warwick 1963b).

THE DECAMETRIC COMPONENT

The first observations of radio emission from Jupiter, and indeed from any planet, were made by Burke & Franklin (1955) at 22.2 MHz. Shortly afterward, Shain (1956) discovered many instances of Jovian activity on records made at 18.3 MHz in 1950 and 1951. He demonstrated the anisotropy of the emission with respect to the System II central meridian longitude. Burke and Franklin (Franklin & Burke 1956, Firor et al. 1955) showed that the radiation is most often circularly or elliptically polarized in the right-hand sense, which suggested a magnetoionic propagation effect in the Jovian ionosphere. This was the first evidence that Jupiter has a magnetic field. It was subsequently found by several groups that the System II rotation period did not fit the decametric observations well over a period of years. By 1962, improved values for the radio rotation period had been published by Shain (1956), Gallet (1961), Burke (1957), Gardner & Shain (1958), Carr et al. (1958, 1961), Smith & Carr (1959), and Douglas (1960a, 1960b, 1962). On the basis of these observations, System III (1957.0), having the rotation period $9^h\ 55^m\ 29^s.37$, was adopted by the IAU for specifying the CML of the radio features of the planet. Warwick (1963a) discovered that there is a tendency for the dynamic spectrum of the radiation to appear in characteristic patterns in the time-frequency plane, and to reappear at later times at nearly the same CML values. Review papers by Douglas (1964), Ellis (1965), and Warwick (1967) are recommended for further background information on the decametric radiation.

Nature of the bursts and storms.—The decameter-wavelength radiation from Jupiter usually consists of noise which is intensity modulated to form randomly occurring bursts. When observed at fixed frequencies, the bursts most often have durations of 0.5 to 5 sec (L bursts). They may occasionally be much shorter (S bursts) or, more rarely, much longer. Typical L-burst envelopes resemble Gaussian functions, more or less, while S bursts may be highly impulsive and sometimes rapidly recurrent. When dynamic spectra are observed, the emission appears to occur for irregular periods on the order of tens of seconds each. These emission periods are known as decasecond bursts. A noise storm is an entire activity period. Noise storms may ordinarily be as short as a few minutes or as long as a few hours. There are usually periods of quiescence between storms which may last for hours, days, or weeks. However, activity may be almost continuous at frequencies of 10 MHz and below (Dulk & Clark 1966), and perhaps also at higher frequencies if very low intensity levels can be detected (Stone et al. 1964, Block 1965). The bandwidths of individual bursts are usually between 0.05 and 2 MHz. At any time during a storm, uncorrelated L bursts may be occurring over a frequency band ranging from 1 MHz to several MHz in width. Over an interval of minutes or hours, the storm mid-frequency can drift upward or downward over a considerable portion of the decametric spectrum.

Average power spectrum.—Decametric activity has been detected at ground-based observatories at frequencies between 3.5 (Zabriskie et al. 1965) and 39.5 MHz (Warwick 1964), with a possible detection at 43 MHz (Kraus 1958). The decametric points in Figure 1 represent averages of flux density over inactive periods as well as active. Near 20 MHz, averages over active periods alone are ~10 times the values indicated (Lebo 1964). However, all such averages vary considerably from one year to another. Burst peak flux densities (L bursts) occasionally exceed values which are 3 or 4 orders of mag higher than indicated in Figure 1 (Carr et al. 1964). It should be emphasized that the average power spectrum during an individual decametric event will appear quite different from Figure 1. The apparent low-frequency cut-off of the decametric spectrum is an effect of the terrestrial ionosphere; at lower frequencies the ionospheric refraction is so extreme that the rays cannot reach the ground. On the other hand, the rapid decrease in flux density with increasing frequency is undoubtedly a property of the source itself. Programs for the observation of Jupiter at frequencies well below the ionospheric critical frequency by means of orbiting radio telescopes are in progress in both the USA and Russia. There may be more power in this part of the spectrum than in the part which has been studied. Observations from spaceships will also permit the mapping of the beam structure of the decametric radiation, the location of source positions, and the direct measurement of Jupiter's magnetic field and magnetospheric plasma parameters.

Longitude distribution of occurrence probability and intensity.—Characteristic histograms of occurrence probability as a function of CML (System III) are shown in Figure 4. The three peaks A, B, and C observed in the vicinity of 18 MHz correspond respectively to regions 2, 1, and 3 of Douglas (1964), and to the main source, the early source, and the third source of Dulk (1965a,b). Note in Figure 4 that while there is a broad region in the vicinity of the CML of the southern-hemisphere magnetic pole which is almost devoid of activity at 18 MHz, there is no such region at 10 MHz. It may also be significant that at the CML of the northern-hemisphere magnetic pole there is a secondary minimum in the 18 MHz histogram, but a maximum in the 10 MHz one. As the frequency is increased above 18 MHz, the probability of occurrence diminishes at all values of CML, but particularly in sources A and C, which become much smaller than B.

Studies of the flux density as a function of longitude at frequencies of 15 MHz and above indicate that on the average, the radiation from source B is much more intense than that from source A (Smith et al. 1965, Register 1968). This is consistent with the dynamic spectrum observations of Warwick (1967).

Effect of Io on occurrence probability.—One of the most important developments in the investigation of the Jovian decametric radiation to date was the discovery of the modulating effect of the satellite Io. Bigg (1964) found that the great majority of the stronger source-B emission events occur when the orbital position of Io, γ_{Io}, is within a few degrees of 93° from superior geocentric conjunction, and that most of the source-A events occur when $\gamma_{\text{Io}} \approx 246°$. Swept-frequency data obtained by Warwick and his associates

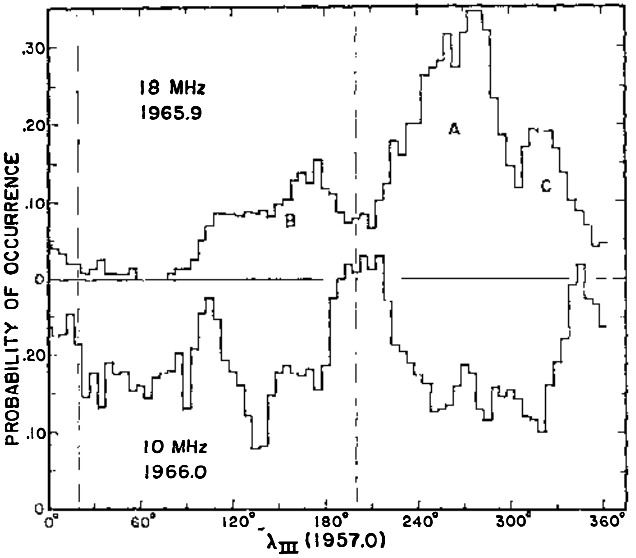

FIG. 4. Histograms of occurrence probability as a function of CML. The CML values of the magnetic poles are indicated by vertical dashed lines. (From Register 1968.)

(Warwick & Kreiss 1964) were used in this analysis. The effect has been verified by several groups (e.g., Lebo et al. 1965, Duncan 1965, Dulk 1965b, McCulloch & Ellis 1966, Riihimaa 1966, Alexander 1967, Barrow 1968) and is well illustrated by the single-frequency data of Register (1968) in Figure 5. It is apparent from the figure that at 20 MHz, most of the source-B emission is Io-dependent, while many of the source-A events depend on Io's position and many do not. Register found that at all frequencies from 18 MHz at least to 27.6 MHz the Io-related source-B ($\gamma_{\mathrm{Io}} \simeq 90°$) and Io-related source-$A$ ($\gamma_{\mathrm{Io}} \simeq 240°$) events are sharply bounded by $\lambda_{\mathrm{III}} \approx 190°$, which is close to the CML of the northern-hemisphere pole. The Io-independent events become fewer relative to the Io-dependent ones as the frequency is increased. Although Io's influence remains strong at frequencies down to 15 MHz (Lebo et al. 1965), it is much less pronounced at 10 MHz (Dulk & Clark 1966, Register 1968).

Characteristic dynamic spectra.—Before the discovery of the influence of Io, Warwick (1963a, 1964) showed that the dynamic spectra of individual noise storms exhibit certain characteristic features which tend to reappear later near the same central meridian longitudes. Dulk (1965a,b) demonstrated that distinctive spectra could be obtained from each of four CML regions, and that the details of each type often depend on the exact position of Io within a certain prescribed range. Three of Dulk's sources correspond

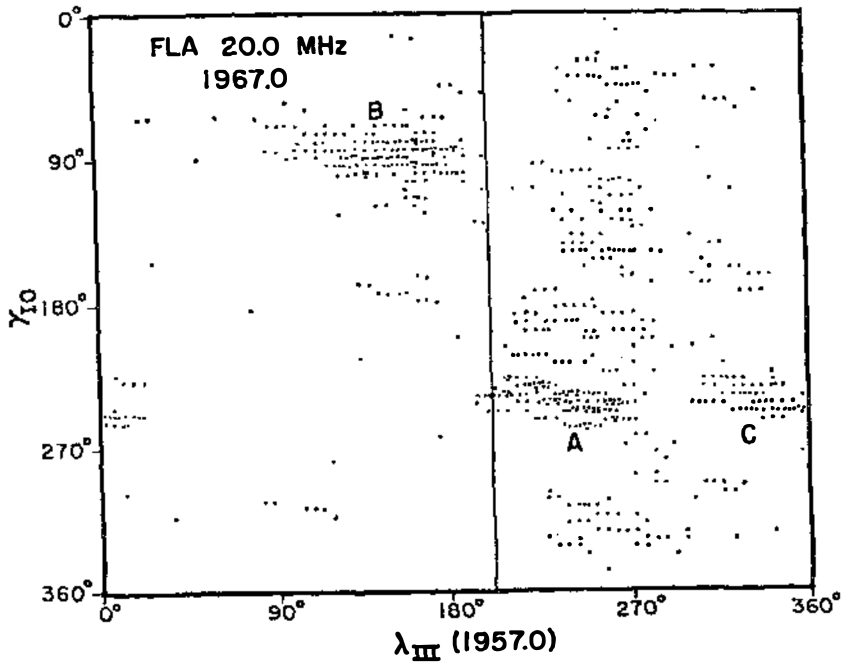

FIG. 5. Distribution of occurrence probability (proportional to density of dots) as a function of the position of Io from superior geocentric conjunction and the CML of Jupiter. CML of northern-hemisphere pole is indicated by vertical line. (From Register 1968.)

to regions previously identified with peaks in the fixed-frequency occurrence probability histograms. Although his fourth source occurs in a longitude zone of low activity ($20° < \lambda_{III} < 80°$, and $\gamma_{Io} \approx 100°$), its distinctive narrow-band spectrum justifies classifying it as a source.

Dulk found the early source *B* highly predictable, occurring almost every time the conditions $80° < \gamma_{III} < 190°$ and $87° < \gamma_{Io} < 96°$ simultaneously prevail. Similar results had been found at fixed frequencies (Lebo et al. 1965; see also Figure 5). The most striking feature of the dynamic spectra observed by Warwick and Dulk is the long, thin arch which sometimes terminates an early-source storm. The position of the arch within the early-source region is a sensitive function of Io's orbital position, as is the maximum frequency attained. This is shown in Figure 6. During such an event the flux density exceeds 10^6 f.u. even at frequencies as high as 39 MHz (Warwick 1967). However, emission was never observed at a frequency higher than 39.5 MHz. It has been suggested that this high-frequency cutoff is approximately the electron gyrofrequency in the part of the emitting region in which the magnetic field is strongest, perhaps close to the surface of the

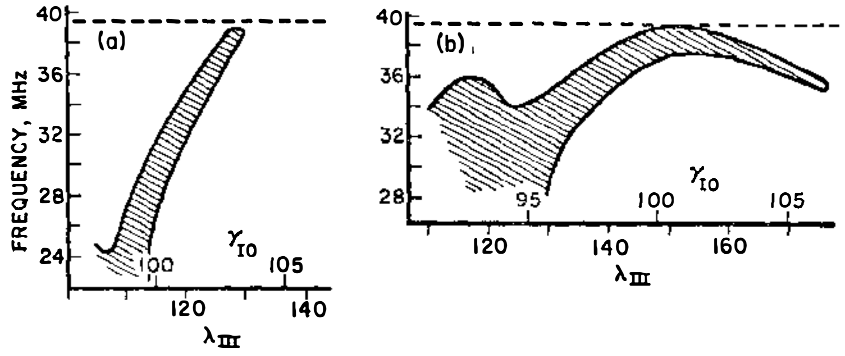

FIG. 6. Tracings of early-source (source *B*) arch in dynamic spectra of Warwick. (*a*) Sept. 17, 1962. (*b*) Oct. 26, 1962. (After Dulk 1965a.)

planet. The other sources displaying characteristic dynamic spectra are the main source, *A* ($190° < \lambda_{III} < 290°$), and the third source, $C(290° < \lambda_{III} < 20°)$, both of which have Io-related ($\gamma_{Io} \approx 240°$) and Io-independent components.

A frequency drift is considered positive if frequency increases with time. It is apparent from Figure 6 that the early-source drift is initially positive, a reversal usually occurring later. On the other hand, the drift of the main source is predominantly negative, although it may sometimes be positive initially (Dulk 1965a). The drifts of the third and fourth sources are negative and positive, respectively.

Warwick (1967) suggests that the dynamic spectra of noise storms are caused by the sweeping of emission beams past the direction of the Earth as Jupiter rotates. He concludes that the beam direction is a function of frequency at a given time, and its width at a given frequency is $\sim 6°$. The repeatability of the beam movements indicates that they are linked to a long-enduring feature of the planet, undoubtedly its magnetic field.

There is a wealth of structural detail which could not be resolved in the noise storm dynamic spectra of Warwick and Dulk. This has been shown by Chatterton (1961), Smith et al. (1963), Riihimaa (1964, 1968a,b,c,d), Block (1965), and Gordon & Warwick (1967). Riihimaa found the dynamic spectra of decasecond bursts to consist most often of parallel but irregularly spaced diagonal bands of emission, separated by 200 to 300 kHz, more or less. The drift rate magnitudes appeared to cluster rather closely about 100 kHz/sec, although the direction of drift usually depended on the CML. Practically all of the positively drifting bands were from source *B*, while almost all of the source-*A* events were negatively drifting. There was apparently no correlation of these drifts with Io's position. Although the decasecond burst drift rates observed by Riihimaa are almost 2 orders of mag higher than those of Warwick and Dulk for storms as a whole, the prevailing directions of drift for sources *A* and *B* for the two sets of observations are in agreement. The surface representing radiation intensity as a function of both time and frequency apparently has several types of structure. For example, there are the diagonal ridges corresponding to the drifting decasecond bursts. There must be in addition an extremely choppy substructure superimposed upon the ridges which gives rise to the L bursts at fixed frequencies. It is known that most of the L-burst structure is impressed after the radiation leaves Jupiter (Douglas & Smith 1967).

Some of the dynamic spectra of Gordon & Warwick and of Riihimaa displayed evidence of unresolved structure on a millisecond time scale. These millisecond bursts, as they were called, were believed to be due to emission bands $\sim$50 kHz wide drifting negatively at rates of $\sim$25 MHz/sec. These drift rates are $\sim 10^4$ times as high as the drifts of storms as a whole. Slee & Gent (1967) and Riihimaa (1968b) suggested that S bursts are produced by the passage of the fast-drift emission bands across the fixed reception band.

S bursts.—The L-burst waveform is impressed upon bursts that were originally much longer than L bursts by diffraction effects in the interplanetary medium (Douglas & Smith 1967). The S-burst waveform, on the other hand, is presumably of Jovian origin (Gallet 1961, Kraus 1958). The durations of individual S bursts generally range from $\sim$20 μsec (Flagg & Carr 1967, Flagg 1967) or less, to several hundredths of a second (Brown et al. 1968). At times they are quasiperiodic, displaying for intervals of a second or so remarkably regular repetition rates between 4 and 40 per sec (Carr et al. 1964, Torgersen 1968, Paul & Carr 1969). In some cases Torgersen noted a sawtooth waveform with a period of $\sim$0.1 sec, each cycle consisting of a gradual rise in intensity abruptly terminated by a precipitous drop. More often, S bursts are entirely sporadic, occurring at highly irregular intervals ranging from milliseconds or less to seconds. Although the intensities of sporadic S-burst peaks often appear to be comparable with those of average L bursts (Paul & Carr 1969), they occasionally increase to 10 or perhaps 100 times their normal intensity within relatively short periods of time.

Riihimaa (1964, 1966), Olsson & Smith (1966), and Baart, Barrow & Lee (1966) have shown that the ratio of the abundances of S to L bursts is much greater for sources B and C than for source A. Slee & Gent (1967) found no time delays corresponding to projected solar-wind velocities when S bursts were received with pairs of antennas separated by distances $\sim$1 km. Block et al. (1969) found a high degree of detailed waveform correlation when individual S bursts were observed simultaneously at two stations separated by 900 km, and no significant time shift (0.5 msec timing accuracy) other than that due to wavefront geometry. These results lead to the conclusion that the S-burst waveform originates at Jupiter rather than in the interplanetary medium or in the terrestrial ionosphere.

Slee & Gent (1967) and Paul & Carr (1969) have demonstrated that the S bursts observed at fixed frequencies are indeed the same phenomena as the unresolved "millisecond pulses" in the dynamic spectra of Riihimaa and of Gordon & Warwick. Paul & Carr observed S bursts from source B with two narrowband receivers separated in frequency by 50 kHz near 20 MHz. In every case in which the burst shapes were similar at the two frequencies (which was relatively infrequently) there was a time shift indicating a negative frequency drift. The average drift rate was -18.6 (± 3.7) MHz/sec (negative), and the average duration of the S bursts in this group was 16.0 $\pm$(2.2) msec. This drift rate is in reasonable agreement with the estimates which have been made from dynamic spectra. From the measured S-burst duration, we deduce that the width of the drifting emission band must have been ~300 kHz, a value in agreement with previous measurements of maximum S-burst correlation bandwidths by May (1965). There is usually little correlation between S bursts observed at frequencies separated by more than 300 kHz.

Typically, a sporadic S burst appears to be composed of quasigaussian noise which is "gated on" for only a very brief interval (Paul & Carr 1969). Although usually relatively gradual, the buildup and decay of the burst can be extremely abrupt. Flagg & Carr (1967) and Flagg (1967) have made high-resolution fixed-frequency recordings of S bursts achieving a time resolution of 10 μsec (100 kHz receiver bandwidth). Occasionally, millisecond bursts were observed in which full intensity was reached within 10 μsec, and the termination was equally abrupt. A number of instances of completely isolated bursts of only 20 μsec duration were observed. This is close to the length of the shortest Jovian burst which can be observed with a 22 MHz receiver of any bandwidth. Even though shorter bursts might be emitted, none shorter than about 5 or 10 μsec can be observed on Earth at 22 MHz because of excessive dispersion in the interplanetary medium over the required receiver bandwidth. We can speculate that the observed 20 μsec burst results from a single elementary emission event of the smallest scale.

One of the features of the theory proposed by Ellis (1962, 1963) and Ellis & McCulloch (1963) is the emission of decametric radiation at frequencies just above the local gyrofrequency by groups of coherent electrons ascending from a low mirror point in Jupiter's magnetic field. The rate of change of the emitted frequency at the distance r from the magnetic dipole would be given approximately by $d\nu/dt \approx -3v_L\nu_H/r$, where ν_H is the electron gyrofrequency and v_L the longitudinal component of velocity of the electrons. Before the discovery of the S-burst frequency drifts, Ellis (1965) predicted that bursts might be found having negative frequency drifts of about 36 MHz/sec (corresponding to $v_L \approx 0.15c$). The predicted drift is of the same order of magnitude and sign as the observed S-burst drifts, a circumstance which would seem to lend support to this feature of the Ellis theory. The theory also assumes that the radiation from a group of electrons is concentrated on the surface of a cone, whose axis is aligned with the magnetic field. Riihimaa (1968a) suggested that the length of time during which a particular drifting S-burst emission band retains its identity is that required for the conical sheet of radiation to sweep past the Earth as the emitting electrons ascend along a curved field line. Assuming that this time is $\sim$0.05 sec, and that the field line is one of those passing close to Io, Riihimaa determined the angular thickness of the conical sheet to be $\sim 1°$. Goldreich & Lynden-Bell (1969), on the other hand, assume that the duration of the drifting S burst is the lifetime of the coherence of the electrons in the radiating group.

Gordon & Warwick (1967) have suggested that each S burst results from the sweeping of a very narrow beam past the Earth as Jupiter rotates, the beam being one of the emission lobes from a very large phase-coherent source. The required source aperture is given roughly by $L \approx \lambda/(\Omega t)$, where λ is the wavelength, Ω the angular velocity of the rotating beam, and t the duration of the S burst. Thus for $t=1$ msec and $\Omega = 1.7 \times 10^{-4}$ sec^{-1}, L is of the order of magnitude of the diameter of the planet. This appears to be completely unrealistic. However, if such narrow sweeping beams do exist they will probably be detected by long-baseline interferometer experiments which are planned by several groups (some already in progress).

Source size.—Upper limits on the sizes of the sources of individual Jovian emission events have been determined with long baseline interferometers. Extensive measurements by Slee & Higgins (1966) at 19.7 MHz with baselines up to 200 km indicated source sizes mostly in the range 10–15 sec of arc. They were also able to show that there was no shift as large as 0.1 planetary diam in the position of the centroid of the emitting region over intervals of at least 2 min. Most of the observations were during periods of L-burst activity. Dulk et al. (1967), using a 34 MHz interferometer of the post-detector correlation type having a baseline of 175 km, found the sources of both L and S bursts to be <3 sec of arc. Subsequent work by Dulk and his associates (Dulk 1968) has indicated source sizes <1 sec of arc. Brown et al. (1968) and Block et al. (1969) have observed individual S bursts at 18 MHz with interferometers having north-south baselines up to 880 km. Some of the measurements indicated sources as small as $\sim$1 sec of arc. As Slee & Higgins have pointed out, the measured source size is probably much larger than the true size because of the effect of scattering by inhomogeneities in the interplanetary medium.

Neglecting degradation by the propagation medium, the width of the smallest phase-incoherent Jovian sources which could be resolved at decameter wavelengths with the longest possible terrestrial interferometer baseline is $\sim$100 km, corresponding to an angular diam of $\sim 0.1''$. The actual resolution limit may be somewhat greater than this because of interplanetary scattering. On the other hand, if the sources are truly phase-coherent, interferometers cannot be used to determine their sizes (Dulk et al. 1967). However, phase-coherent sources larger than 10 or 100 km would seem to be a virtual impossibility. We conclude from the observations which have been made that at least some of the Jovian sources are smaller than 1000 km in width, and may be smaller than 100 km.

Polarization.—Measurements of all four polarization parameters have

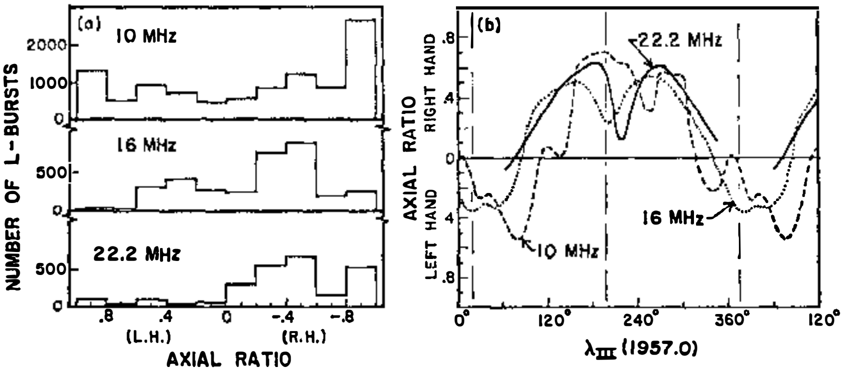

FIG. 7. (*a*) Distributions of values of apparent axial ratio for *L* bursts in 1965. (*b*) Smoothed distributions of average *L* burst axial ratio per 10° interval of CML. Vertical dashed lines indicate CML values of magnetic poles. (From Kennedy 1969.)

been made by Sherrill (1965) and Barrow & Morrow (1968). Sherrill concluded that the polarization fraction is usually at least 0.8 above 15 MHz, and is practically 1.0 above 20 MHz. However, most of the published data on the axial ratio of the polarization ellipse were determined from measurements of the circular components alone, and are necessarily based on the assumption of complete polarization. In the light of the results of Sherrill and of Barrow & Morrow, this is a reasonably valid assumption above 15 MHz.

The distributions of apparent axial ratios at 22.2, 15.9, and 10 MHz are shown in Figure 7a, assuming complete polarization. Errors introduced by this assumption are such that the true distributions would be shifted somewhat toward the axial ratio values +1 and −1, particularly at 10 MHz. It can be seen that the polarization is almost always right-hand at 22.2 MHz [and also at higher frequencies, as noted by Barrow (1963)]. The left-hand circular component becomes relatively more prominent as the frequency is reduced, but the right-hand component is still predominant down to 10 MHz, or perhaps lower.

The average apparent axial ratio also varies with CML, as indicated in Figure 7b. Although at 22.2 MHz most of the bursts are right-hand elliptically polarized, the relatively small number of left-hand ones which do occur are usually found in the CML region between about 0° and 60°. As the frequency is reduced, the CML range within which the polarization is left-hand broadens, until at 10 MHz the left-hand zone is almost as wide as the right-hand one.

In most of the emission mechanisms proposed for the decametric radiation (see later section on emission mechanisms), the radiation leaves the emission region in the extraordinary mode at a frequency just above the local electron gyrofrequency (and considerably above the local plasma frequency). The polarization would in general be elliptical, the electric vector having the same rotational sense as that of the electronic circulation about the magnetic field. The shape of the polarization ellipse would depend most strongly on the direction of the magnetic field relative to that of propagation, being circular for longitudinal propagation and linear for transverse (limiting cases). As the wave propagates out through the magnetosphere, it would remain entirely in the extraordinary mode, provided it encounters no abrupt changes in electron density or magnetic field (i.e., no appreciable variation over a distance on the order of a wavelength). As long as the electron density remains appreciable, the axial ratio would continually change along the propagation path. The value at each point would be determined largely by the relative direction of the field at that point. The polarization sense, however, would remain constant, since generally there will not be a reversal in the parallel field component at any point along a ray path. The final axial ratio of a ray which has completely escaped from Jupiter's environment would thus be determined by the relative field direction in the region in which the electron density became negligible (Pawsey & Bracewell 1955).

It is significant in the light of the foregoing discussion that in Figure 7b the center of the zone of right-hand polarization is close to the CML toward which the northern-hemisphere pole is tipped, while the CML of the southern-hemisphere pole is near the mid-longitude of the left-hand polarization zone. Occurrence probability histograms (e.g. Figure 4) indicate that beaming effects are more pronounced at higher than at lower frequencies. Thus the relative deficiency of left-hand polarization at the higher frequencies can be attributed to an asymmetry in the beams escaping from the northern and southern hemispheres, the latter hardly ever being in the direction of the Earth. It is believed that the dip which occurs in each of the curves of Figure 7b near the CML of the northern-hemisphere pole is significant, although no explanation of it is offered (Kennedy 1969).

It was deduced from decimetric observations that the pole which is tipped toward the Earth near a CML of 200° is in the northern hemisphere. With the assumption that the region of emission of decametric radiation is relatively close to this pole, the predominant right-hand polarization sense indicates that this is the pole from which magnetic-field lines emerge (Dowden 1963, Warwick 1963b). A compass on Jupiter would thus point south. The same conclusion was reached by Berge (1965) from his observation of the circularly polarized component of the decimetric radiation.

Gordon & Warwick (1967) observed one instance of *S*-burst activity during which the dynamic spectrum displayed an apparent alternation of polarization sense as a function of frequency, referred to as "polarization diversity." They interpreted this as a form of Faraday effect caused by the difference in propagation velocity of two elliptically polarized characteristic modes in Jupiter's magnetosphere. Torgersen (1968) made recordings of the circularly polarized components at a fixed frequency but with a time resolution of 0.2 msec, more than an order of magnitude smaller than that of Gordon & Warwick. He most often found the circular components to be correlated on this time scale for both L and S bursts. However, occasionally during an S-burst storm, the circular components would become uncorrelated for brief intervals, and sometimes anticorrelated, tending to confirm the result of Gordon & Warwick.

If the interpretation of the polarization diversity effect by Gordon & Warwick is correct, there must sometimes be a coupling of energy from the extraordinary mode into the ordinary mode, as they have suggested. This would presumably occur within a so-called stop zone (Cohen 1960, Gulkis & Carr 1966a, Dulk 1967) immediately adjacent to the emission region, or at some plasma density discontinuity farther out in the magnetosphere.

Warwick & Dulk (1964) had previously searched their dynamic spectra for a component of the Faraday rotation of the major axis of the polarization ellipse which might be attributable to Jupiter's magnetosphere. After correcting for the Faraday rotation in the terrestrial ionosphere, no residual rotation could be detected. Warwick (1967) interpreted this negative result as excluding a plasma density >10 cm^{-3} at a distance of 1 radius from the surface of Jupiter. However, this deduction is based on the assumption that mode coupling exists. It is not clear that this assumption is necessarily correct.

The Io-related emission probably originates from some point in the flux tube passing through or near Io itself, as has been widely suggested. In this event, the source-B radiation must propagate initially transverse to the field, and that from source A nearly so. The characteristic polarization for the extraordinary mode is linear when propagation is transverse to the field. However, Dulk (1967) has pointed out that as such a ray propagates out through the magnetosphere toward the Earth the field becomes more nearly aligned with the ray path, giving rise to the elliptical polarization actually observed. The fact that Figure 7a indicates a higher proportion of purely circularly polarized events at 10 MHz than at 22.2 MHz appears significant, suggesting the alternative possibilities that either (a) emission at 22.2 MHz, being more Io-dependent, occurs farther out from the limb of the planet than that at 10 MHz, or (b) the 10 MHz radiation is affected by the diminishing plasma out to a greater distance in the magnetosphere, where the field is more nearly parallel to the propagation path.

Decametric rotation period and the 12-year cycle.—There is often a large variation in the general level of activity over a period of several years. Gallet (1961) suggested an anticorrelation with the smoothed sunspot number, and later observations seemed to bear this out (Smith et al. 1965). However, there is also the possibility that the effect is due to the change in D_E (the Jovicentric declination of the Earth), since the periods of the sunspot cycle ($\sim$11 years) and Jupiter's orbital motion (11.9 years) are so nearly the same (Carr 1962, Douglas 1964). The fortuitous phase relationship between the time variations in D_E and sunspot number in recent years has made it particularly difficult to determine which is responsible. Carr (1962) mentioned the possibility that it was the tilt of the active northern hemisphere away from the Earth (i.e., D_E at its southerly maximum) in 1958, and not the sunspot number maximum, which was the cause of the observed minimum in decametric activity at that time.

An apparent increase in the decametric rotation period by about a second in 1961 was reported by Douglas & Smith (1963) and Smith et al. (1965). Gulkis & Carr (1966b) assumed that the apparent rotation period actually undergoes a slight sinusoidal variation with a period of 11.9 years, Jupiter's orbital period. Thus, by comparing the CML of source A at 18 MHz in 1951 (Shain 1956) with that in 1963 (Smith et al. 1965), they were able to determine an average value over one cycle. Their result, $9^h\ 55^m\ 29^s.67$, is in good agreement with the decimetric determination of Komesaroff & McCulloch (1967), $9^h\ 55^m\ 29^s.83$. Gulkis & Carr attributed the variation to a geometrical beaming effect. Donivan & Carr (1969) have made an independent determination over a period of almost 12 years, using the 1955 source-A position of Gardner & Shain (1958) near 20 MHz and that obtained in 1967 by the University of Florida group. The new value is $9^h\ 55^m\ 29^s.73$, in excellent agreement with the previous one. Figure 8 compares the correlation of the source-A position vs. D_E with that of the source position vs. sunspot number. The CML values, designated λ_{III} (1967.0) in the figure, are based on the new value of the rotation period. The evidence is clearly in favor of the idea that the apparent rotation period variation is a geometrical

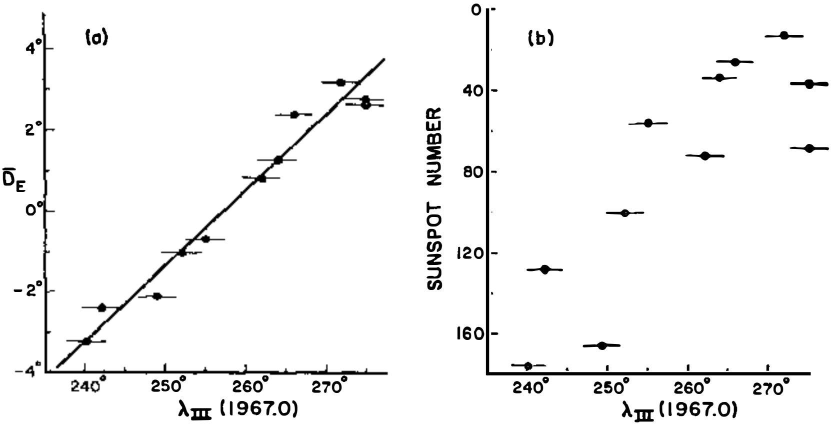

FIG. 8. (a) Correlation of mean values of D_E for each apparition with CML values of the center of source A at 18 MHz. (b) Relatively poor correlation of averaged sunspot number with the CML of source A. CML values are based on a rotation period of $9^h\ 55^m\ 29^s.73$. University of Florida–University of Chile data were used for all points except that for λ_{III} (1967 0) = 275°, which was from Shain (1956). (From Donivan & Carr 1969.)

effect, rather than a result of change in solar activity. It seems most likely that the long-term variation in activity level is also mainly a geometrical effect, although the poorer propagation conditions at higher sunspot numbers undoubtedly contribute to some extent.

A geometrical model for radiation beaming.—One of the earliest theories of the origin of the Jovian decametric emission, that of Warwick (1961), was based on the production of radiation by electrons which had precipitated into the ionosphere from the Van Allen belt. Soon after the discovery of the Io effect by Bigg (1964), it appeared obvious to several groups that much of this precipitation (or of some other type of radiation-producing disturbance) might occur near the foot of the magnetic flux tube which had been disturbed by the passage of Io. It followed that the source-B radiation must be beamed at $\sim 90°$ with respect to the field direction at the emission point, and at a somewhat smaller angle in the case of the Io-related component of the source-A emission. The simplest geometrical model seemed to be one in which radiation is concentrated in directions near the surfaces of very wide-angle cones, whose axes are aligned with the field near the respective intersections of the Io flux tube with the ionosphere. However, many key questions were left unanswered by these rudimentary ideas (Dulk 1965a, Carr et al. 1965, Davis 1966, Roberts & McCulloch 1966).

Dulk (1967) and Piddington (1967) have developed more detailed geometrical models for the beaming of the source-B emission and the Io-related part of that from source A. The two models are similar. Dulk assumes (as does Piddington) a somewhat distorted dipole field, with the north pole tipped 10° toward Jupiter's 200° meridian. Once each 13 hr, when Io is near the 200° meridian (but only then), radiation is beamed into a conical sheet of half-angle $\chi = 79°$. The cone axis lies along the field direction close to the intersection of the Io flux tube with the ionosphere in the northern hemisphere. Source B is observed when the leading limb of the conical sheet sweeps across the Earth, and Io-dependent source A appears when the opposite limb sweeps past. For an undistorted dipole field, this model would predict the CML values of the sources to be $\sim 125°$ for B and 275° for A, and the Io positions from superior geocentric conjunction, γ_{Io}, to be $\sim 105°$ for B and 255° for A. The slight discrepancies between these values and the observed ones are attributed to field distortion and to the stimulation of emission from an extensive region rather than from a point.

Dulk's model predicts a small-amplitude sinusoidal drift in the CML of source A due to the variation in D_E, with a period of 11.9 years. There would be a similar drift in the CML of source B, but in the opposite phase. Dulk's predicted sinusoidal drift for source A was much smaller than that shown to exist by Gulkis & Carr (1966b). Dulk assumed that the angle σ between the field direction at the foot of the Io flux tube and the direction of Jupiter's rotational axis is 47°. This value was obtained by assuming a dipole field configuration for the flux tube through Io. However, Donivan & Carr (1969) found that by adjusting the values of both χ and σ, the observed sinusoidal drift of source A could be obtained. They used the relationship

$$\cos(\lambda_A - \lambda_0) = (\cos\chi - \cos\sigma \sin D_E)/(\cos D_E \sin\sigma) \qquad 4.$$

where λ_A is CML of the center of source A, and λ_0 is 211°. Values of 78 and 18° for χ and σ, respectively, together with the ephemeris values of D_E, yielded a time variation of λ_A remarkably close to that observed from 1951 through 1967 (provided the same CML system is used as in Figure 8). Such a value of σ would represent a distortion of $\sim$30° in the direction of the field line.

Source B shows very little sinusoidal longitude drift (Donivan & Carr 1969). The small amount it does display is in phase with that of source A, instead of in antiphase as predicted by Dulk's model. Although the model is successful in several respects, the failure to account for the drift pattern of source B appears to be a serious difficulty.

THEORETICAL INVESTIGATIONS

Although the basic mechanisms of the decimeter and centimeter wavelength radio emissions from Jupiter are well understood, the decameter wavelength phenomena appear to be complex, and may not be fully explained for many years. Recent advances in the theory of Jupiter's magnetosphere, however, may well form a sound basis for subsequent more detailed theories accounting for all of the observed phenomena. A discussion of parameters related to the structure and energetics of the Jovian magnetosphere, including recent theoretical work, is included in this section.

Ambient Conditions

Ambient conditions surrounding the Jovian magnetosphere are generally estimated by extrapolating the solar wind parameters from 1 to 5 a.u. This implicitly assumes that the solar wind extends radially at least as far as Jupiter's orbit. The supersonic flow of the solar wind is currently believed to terminate in a shock transition in the solar system somewhere between 5 and 50 a.u. (Hundhausen 1968). If it terminates near or before 5 a.u., then estimates of the ambient conditions based on this extrapolation may be grossly in error. One objective of the first Jupiter space probe will be to test this assumption. At the Earth's distance from the Sun, the quiet solar-wind plasma consists primarily of ionized H moving radially from the Sun with average speeds of 300–500 km/sec with densities of $\sim$10 ions cm^{-3}. Imbedded in the solar wind is a magnetic field whose strength is $\sim 5\times10^{-5}$ G. At Jupiter's orbit (5 a.u.), it is expected that the solar-wind velocity will be about the same as that near the Earth but the density will be reduced by the square of the distance from the Sun, a factor of $\sim$25. Because of the Archimedian structure (Stern 1964) of the solar magnetic field, the magnetic field strength is estimated to fall off nearly linearly between 1 and 5 a.u. Thus in the ambient plasma of Jupiter, the estimated average quiet solar-wind parameters are a velocity of $\sim$400 km/sec, a density of 0.2 to 0.3 ions cm^{-3} and a magnetic-field strength of 10^{-5} G. If the temperature in the solar corona falls off with distance from the Sun according to Chapman's (1959) static model, $T::R^{-2/7}$, then for a temperature of $10^{6°}$ K in the solar corona, the corresponding thermal plasma temperature is $10^{5°}$ K at Jupiter's orbit. By comparison, the mean translatory kinetic temperature of a proton in the solar wind is $\sim 10^6$ to $10^{7°}$ K.

Factors Affecting the Distribution of Ionization

Corotation.—The rapid rate of rotation of Jupiter and its large size suggest that rotational effects are likely to be of utmost importance on Jupiter. In his review paper on Jupiter in 1965, Ellis emphasized the necessity of investigating the properties of a rapidly rotating magnetosphere. He pointed out that the centrifugal forces imposed by rotation could be important in determining the distribution of plasma throughout most of Jupiter's magnetosphere, provided that it was corotating with the planet. This subject has been given considerable attention in recent years.

Magnetospheric rotation is believed to be imposed by the rotation of the ionosphere, which in turn is driven from below by atmospheric viscosity. Gledhill (1967) has recently published a review of this topic. In the simplest model, the planet including the neutral atmosphere and the base of the ionosphere is considered to be a conducting sphere of radius R_0, rotating with an angular velocity $\bar{\Omega}$ in a magnetic field $\bar{H}$ (Hones & Bergeson 1965). An electron with charge q situated at a point $\bar{R}$ in the sphere moves with an angular velocity $\bar{v} = \bar{\Omega} \times \bar{R}$, and experiences the Lorentz force

$$\bar{F} = \frac{-q(\bar{\Omega} \times \bar{R}) \times \bar{H}}{c} \qquad 5.$$

This force causes the charges to redistribute themselves in such a way as to create electric fields and electrostatic forces causing the net force on each electron to vanish. The resultant potential at the surface of the sphere serves as a boundary condition for the potential outside the sphere. By assuming that the sphere and magnetic field are imbedded in a plasma in which the conductivity is infinite along the lines of force and is zero in a direction perpendicular to the lines, Hones & Bergeson have shown that for a dipole field the resultant electric field $\bar{E}$ in the plasma gives rise to a drift velocity exactly that required for corotation. The result holds whether or not the dipole axis is aligned with the rotational axis. Melrose (1967) has generalized the analysis to allow for nondipole lines, provided that they are fixed to the magnetic axis. The conclusion reached is that the magnetosphere should corotate with the planet until one or more of following circumstances are met (Gledhill 1967):

(*a*) the plasma density decreases to such a low value that components of the electric field can exist along the magnetic lines of force;

(*b*) the plasma becomes so dense that it conducts well across the lines of force;
(*c*) the currents due to differential motion of particles of different sign distort the magnetic field appreciably;
(*d*) viscous interactions near the outer boundary retard the motion;
(*e*) the plasma density becomes too low to maintain the space charge required to produce the electric field necessary to drive the rotation.

Because Jupiter has different rotation periods at different latitudes, there is a velocity slip between the equator and the higher-latitude regions which amounts to ~7 deg/day. If this is transmitted to the ionosphere, some differential rotation might also exist in the magnetosphere.

Potential along a field line.—The basic problem of how rotation modifies the hydrostatic distribution of ionization along a magnetic-field line was treated by Angerami & Thomas in 1964. Later Ellis (1965), Melrose (1967), Gledhill (1967b), Piddington (1967), and Brice (1968) considered the problem with specific reference to Jupiter. It is generally agreed among the authors that the magnetosphere can be considered to be divided into two regions, one dominated by gravitational forces and the second dominated by centrifugal forces.

The fundamental relationships can be demonstrated by considering the combined gravitational and centrifugal forces, $\overline{F}_g$ and $\overline{F}_c$ respectively, acting on the unit mass shown at point $P(r, \theta)$ in Figure 9. It is readily shown that the resultant force $\overline{F} = \overline{F}_g + \overline{F}_c$ may be derived from the scalar potential

$$V = -g\frac{R_J^2}{R} - \frac{1}{2}\Omega^2 R^2 \sin^2\theta + \text{const} \qquad 6.$$

where g is the gravitational force acting on a unit mass at the radius R_J, and Ω is the angular velocity of rotation of the planet. If it is assumed that the charged particles in the magnetosphere are constrained to move along dipole magnetic-field lines of force somewhat like threaded beads moving on a wire, the potential along a particular field line which passes through the equator at $r = L$ is given by

$$V = gR_J\left[1 - \frac{1}{r}\right] + \frac{1}{2}\frac{\Omega^2 R_J^2}{L}\left[1 - r^3\right] \qquad 7.$$

where $r = R/R_J = L\sin^2\theta$ is the equation of the dipole field line. The constant term has been chosen so that the potential on the surface ($r = R/R_J = 1$) is zero. Above the surface of the planet the potential V along this field line at first increases to a maximum at

$$r = \left[\frac{2}{3}\frac{Lg}{\Omega^2 R_J}\right]^{1/4} \qquad 8.$$

and then decreases to a minimum in the equatorial plane. The surface formed

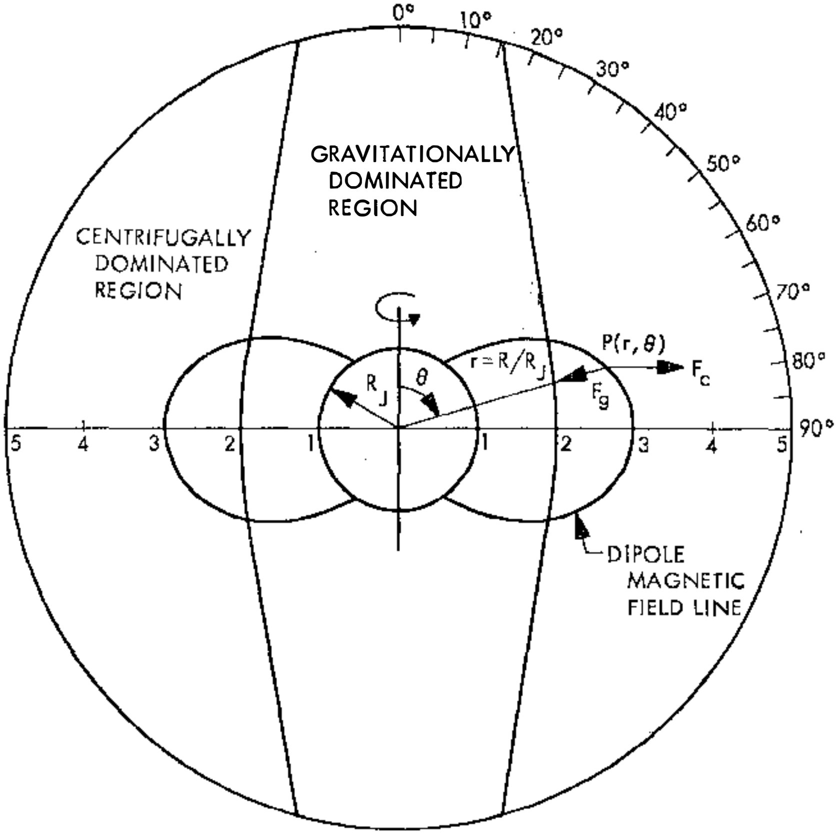

FIG. 9. A plot of a section of the Jovian magnetosphere showing the division into a gravitationally and a centrifugally dominated region. The outer circle is drawn at an arbitrary distance from the planet and does not represent the entire extent of the magnetosphere.

by the points of maximum potential divides the magnetosphere into two regions on the basis of the dominating force. Figure 9, drawn to scale, shows the boundary between the gravitationally and centrifugally dominated regions. The division occurs close to 2 Jupiter radii in the equatorial plane.

Plasma may be trapped either in the gravitationally dominated region close to the planet or in the centrifugally dominated region in the outer magnetosphere. Particles of sufficient energy may pass freely from one region to the other. The energy required to raise a proton from the surface of Jupiter to the peak of the potential barrier is $\sim$5 eV, corresponding to a kinetic temperature of nearly $5 \times 10^{4\circ}$ K. Magnetospheric models in which the source of the plasma is the thermal ionospheric plasma require very high temperatures in order to populate substantially the centrifugally dominated region.

Ring current.—The centrifugal force imposed by corotation has the tendency to fling the particles along the field line toward the equatorial plane where the potential is minimum. In the absence of an inverse pressure gradient in the centrifugal region, the net effective force will cause the charged corotating particles to drift in a direction perpendicular to both the magnetic field and the force. The resultant flow is a ring current (Piddington & Drake 1968). Such a ring current in the magnetosphere would distort the magnetic field by reducing it inside the ring and increasing it outside. The distortion becomes more severe as the current density increases, which suggests that there is an upper limit to the plasma density that can corotate at any distance from the rotational axis. Hines (1964) has shown that serious distortion of the assumed dipole configuration occurs at a distance at which the kinetic energy density of the gas becomes comparable to the magnetic energy density. In the equatorial plane, the maximum density N_M of plasma which can corotate is related to the radial distance r by the expression

$$rN_M^{1/8} \approx \left[\frac{3H_0^2}{4\pi m\Omega^2 R_J^2}\right]^{1/8} = \text{const} \qquad 9.$$

where m is the mass of an ion, and H_0 is the magnetic-field strength in the equatorial plane at $r = 1$. When this density is exceeded, at a given distance r, the field becomes greatly distorted, and the plasma may break away from the main field (Dungey 1958). This limit is illustrated for different values of H_0 by the parallel slanting lines in Figure 10. Although the figure shows that very high densities could corotate, nothing is specified about the production of such high densities or about the stability of the ring current. The high density limit forms a basis for one theory of decameter emission (Gledhill 1967a).

The Outer Boundary

The earliest theoretical work on the size of the magnetospheric cavity (Ellis 1963, Carr et al. 1964) considered the confinement of Jupiter's magnetic field to be due to the interplanetary plasma, by analogy with current theories on the boundary of the Earth's magnetosphere. At the cavity boundary, the solar-wind pressure is balanced by that exerted by the magnetic field inside. With the assumption that the field is nonrotating, the expression for the radius of the cavity in the equatorial plane is given by (e.g. Hess 1968)

$$\frac{R}{R_J} = \left[\frac{H_0^2}{4\pi mnv^2}\right]^{1/6} \qquad 10.$$

where v is the solar-wind velocity, m is the mass of a proton, n is the proton density and H_0 is the magnitude of the surface equatorial field. Substituting values of $v = 400$ km/sec and $n = 0.25$ protons cm^{-3}, and $H_0 = 10$ G, into this expression yields a distance of $R \sim 50\ R_J$. The corresponding value for the Earth is only 10 Earth radii. Balancing the thermal pressure alone against the magnetic pressure leads to a distance of $R \sim 100\ R_J$ suggesting that the

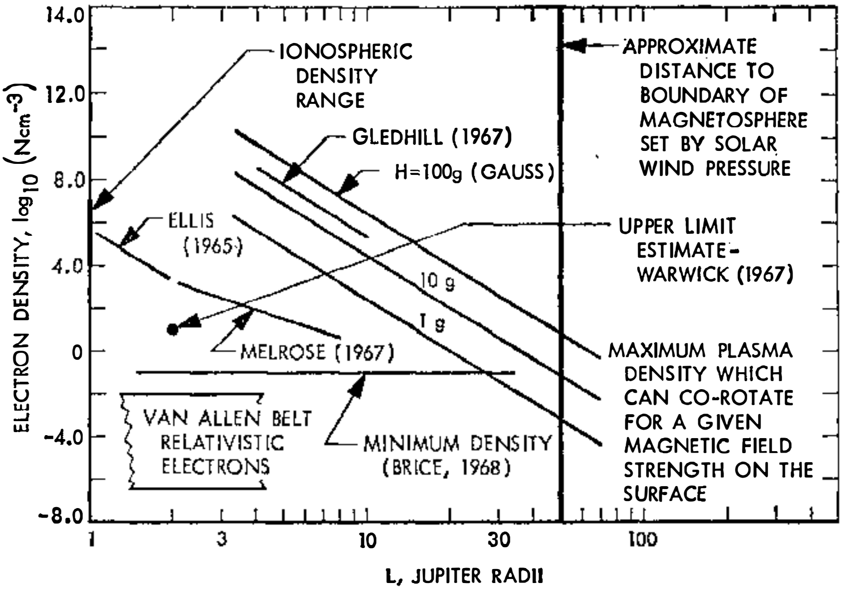

FIG. 10. The logarithm of the electron density plotted as a function of distance in the equatorial plane for a number of theoretical models.

tail of the magnetosphere will not be much less than 100 R_J and may actually extend farther. Note that Jupiter has five satellites which lie within 50 R_J and thus move through the region controlled by Jupiter's magnetic field. For comparison, the mean distance of the Moon from the Earth is 60 R_e which lies well outside the magnetosphere.

The more recent work of Ellis (1965), Gledhill (1967b), Piddington (1967), and Melrose (1967) suggests that if the ring currents are large enough to distort the dipole field configuration seriously, the boundary may occur closer to the planet. Although the high-energy relativistic electron density is too small to produce appreciable field distortion, a lower-energy thermal component could (e.g. Figure 10).

Thermal Plasma

Origin.—Upward diffusion of protons and electrons from Jupiter's ionosphere could provide a source of thermal plasma to the magnetosphere. The key parameter to the extent of the plasma, if it is ionospheric in origin, is the temperature and hence the scale height. A quantitative condition that the thermal ionospheric plasma be trapped in the potential well close to the surface of the planet is that its mean translatory kinetic energy be much less than the height of the potential barrier. This condition may be expressed as

$$\tfrac{3}{2}kT \leq \tfrac{1}{2}mgR_J$$

where k is Boltzmann's constant, g is the acceleration due to gravity, and T is the kinetic temperature of the particle with mass m. The inequality leads to the estimate that for temperatures $\lesssim 10^{3°}$ K, the ionospheric plasma would be confined to the gravitationally dominated region shown in Figure 9, whereas for temperatures $\gtrsim 10^{4°}$ K, it would freely escape into the centrifugally dominated region.

The most thorough analysis to date of the Jovian ionosphere is that of Gross & Rasool (1964). These authors have theoretically investigated the vertical temperature profiles in the atmosphere above the clouds and the structure of the ionosphere for two model atmospheres in which the hydrogen to helium mixing ratio varies by a factor of 600. The ionosphere is assumed to form on Jupiter because of photoionization of the atmospheric gases by solar ultraviolet and X radiation. The equilibrium electron density is determined by a number of ionizing, recombination, and charge exchange processes which occur within the ionosphere. Maximum electron densities of $\sim 10^6$ cm^{-3} are found to occur at the altitudes of 220 km and 110 km above the cloudtop for the two model-atmospheres studies. In both models, the major ionic constituent of the ionosphere is H^+. Temperatures of $\sim 130°$ K are predicted in the ionosphere. Warwick (1967) has made an independent estimate of the temperature and arrives at a value of 500° K, considerably greater than 130° K, but far from the $10^{4°}$ K required to produce an extensive magnetosphere. For these temperatures, the flux of thermal ionization which escapes into the centrifugally dominated outer region is negligibly small. Brice (1968) has estimated that recombination will limit the density to much less than 0.1 cm^{-3}.

Although it would seem that if the energy input to the ionosphere were limited to solar radiation, the thermal plasma would be confined to the gravitationally dominated region, Brice (1968) proposes that photoelectrons released high in the ionosphere cause a flux of fast (unthermalized) electrons which can contribute significantly to the density in the centrifugal region. He finds that the minimum density in the magnetosphere due to photoelectrons alone will be 0.1 cm^{-3} at a few R_J with an increase to a few tens per cm^3 or higher at some tens of R_J. Piddington (1967) has suggested that there are still other sources for heating and ionizing the Jovian ionosphere, namely hydromagnetic motions which may be produced by large-scale interchange motions. There is also the possibility that ionization in the outer zone could have diffused inward from the ambient plasma.

Experimental results.—To date, there is little experimental data from which the thermal plasma density in Jupiter's magnetosphere can be directly deduced. Warwick (1967) cites the lack of a detectable Jovian Faraday effect in the decametric burst radiation as evidence for excluding a plasma density >10 cm^{-3} at distances ~ 1 radius from Jupiter. This upper limit is shown as a point in Figure 10. This interpretation is open to question since it assumes that mode-coupling occurs at some point in Jupiter's magnetosphere, while there is no proof that mode-coupling exists.

Model requirements.—Warwick argues in favor of a close-in model magnetosphere on the grounds of his Cerenkov decametric emission theory, which requires a low electron density in the upper atmosphere so that the radiation may cross a magnetoionic stop zone and escape from the planet. However, Brice's suggestion (1968) that stop zones would be automatically eliminated by heating from the absorbed radiation would apparently invalidate this argument. A number of authors have proposed magnetospheres with much higher densities on the basis of decameter emission models. For example, Ellis (1965) concludes that the electron density would have to be 3 orders of mag larger than Warwick estimates, and Gledhill (1967a) has proposed a model in which the electron density near Io's orbit radius ($6R_J$) is 10^7 cm^{-3}. The plasma frequency corresponding to the latter electron density would be 35 MHz. The wide range of electron densities suggested by these models and shown on Figure 10 reflects our real uncertainty of the true density.

Energy Considerations

Since the mean decimetric power radiated from Jupiter has not changed appreciably over the last 10 years, it can be inferred that the radiating electrons which form the Van Allen belts are nearly in an equilibrium state or that the total energy content of the belts is so large that after having radiated for 10 years there is no detectable change in the belts. The second alternative does not seem likely since it in turn implies electron energy densities large in comparison to the magnetic energy densities in the magnetosphere. The more attractive alternative is that the radiated power is being continually supplied to the belts in the form of high-energy electrons which either are accelerated locally or arrive in the vicinity of the belts with their full energy. If this hypothesis is correct, it is reasonable to ask about the possible sources of energy which can maintain the belts in equilibrium and supply a power of $\sim 10^9$ W.

The energy supplied to Jupiter's magnetosphere must be carefully distinguished from the energy flux which transverses the entire magnetosphere with little loss in it. Most of the energy carried by the solar radiation flux falls into this latter category. It passes freely through the magnetosphere and is deposited directly in Jupiter's lower atmosphere. The solar radiation flux at Jupiter's orbit is $\sim 0.8 \times 10^4$ ergs cm^{-2} sec^{-1} (Gross & Rasool 1964). The incident energy intercepted by Jupiter's disk is $\sim 10^{17}$ W. Most of this energy is unavailable for direct use in the magnetosphere although it represents the largest known external source of energy to Jupiter. Studies of the thermal heat balance for Jupiter indicate there must be an internal source of energy which supplies power at about the same rate received from the Sun (Öpik 1962, Gross & Rasool 1964). The origin of this energy and hence its availability for use in the magnetosphere is unknown. It has been suggested that it could be energy released by gravitational contraction.

Photoelectrons produced in Jupiter's atmosphere by the incoming solar flux may escape the ionosphere and cause a flux of very fast electrons to enter the magnetosphere. Brice (1968) estimates that the photoelectron flux will be $\sim 10^8$ cm^{-2} sec^{-1} with a mean energy of 10 eV per electron and a total power of $\sim 10^{11}$ W.

The total energy flux input at the top of the Earth's atmosphere due to cosmic radiation is $\sim .004$ erg cm^{-2} sec^{-1} (Leighton 1959). If this same flux reached Jupiter it would carry $\sim 10^{11}$ W into its atmosphere. Chang (1962) has estimated that the relatively strong magnetic field will reduce the flux by a factor of 200, bringing the incident power down to 5×10^8 W. Like the solar flux, only part of this energy is available to the magnetosphere. Field (1959) has estimated that the secondary electrons produced by collisions of the cosmic rays in the atmosphere will have a radially outward energy flux of 3×10^{-6} erg cm^{-2} sec^{-1} or 1.8×10^8 W. Field also estimated that the small fraction of primary cosmic rays which are electrons have an energy flux of 1.8×10^8 W. These estimates are believed to have neglected the magnetic shielding on Jupiter and hence are upper limits.

Lingenfelter et al. (1965) have shown theoretically that the flux of solar neutrons in the vicinity of the Earth is 3×10^{-3} neutrons cm^{-2} sec^{-1}, with energies ranging from 10 to 400 MeV. If the neutrons are emitted isotropically, the flux at Jupiter's orbit will be reduced by a factor of ~ 25 because of its increased distance, and by an additional factor of 3 because the low-energy neutrons will have decayed before they reach Jupiter. The solar neutron spectrum reaching Jupiter is expected to start at ~ 50 MeV and extend up to 400 MeV. If the average neutron energy is 200 MeV, the amount of power intercepted by Jupiter's magnetosphere, assumed to be 50 R_J in radius, is estimated to be 10^8 W.

The kinetic flux of the quiet solar wind at Jupiter's orbit is $\sim 2\times10^{-2}$ erg cm^{-2} sec^{-1}. Assuming that the magnetosphere presents a cross-sectional area equal to $\sim \pi(50\ R_J)^2$, the maximum solar wind power is between 10^{14} and 10^{15} W (Carr et al. 1964, Warwick 1964). The observed stressing of the geomagnetic field during a magnetic storm suggests that ~ 1 per cent of the incident power penetrates the Earth's magnetosphere (Axford 1966). We may suppose as a first approximation that this result holds for Jupiter also. The available power from the solar wind is then estimated to be 10^{12} to 10^{13} W.

The rotational energy of Jupiter is an almost unexplored potential source of power to its magnetosphere. Assuming that the mass distribution in Jupiter is such that the moment of inertia of the planet is given by 0.26 $M_J R_J^2$, then its rotational energy is estimated to be $\sim 10^{35}$ joules. If the present rate of radiation has remained constant for the last 100 years, and is being supplied from Jupiter's rotational energy, then the fractional change in Jupiter's rotation rate would be only 10^{-17}. Such a small change is far below the detectable limit. The transfer of energy, if it takes place at all, is probably effected through the magnetic field. For example, induced electric fields produced by rotation of the tilted-axis magnetic field may under certain circumstances supply energy directly to the electrons in the magnetosphere (Hones & Bergeson 1965).

The satellite Io deserves special consideration because of its role in the low-frequency emissions. The energy in its orbital motion is 10^{31} joules. If it is assumed that the radiated synchrotron power derives its energy from Io with a conversion efficiency of 10^{-5}, the expected change in the period of Io over a 100 year interval is only .006 sec. The three-body commensurability between Io, Europa, and Ganymede (Hagihara 1961) makes this number uncertain, but it is probably an upper limit. It is estimated that a change in period of ~ 1 sec in 100 years would have been detectable.

Cosmic ray, neutron, and backscatter sources would require conversion efficiencies of nearly 100 per cent to supply sufficient power to maintain the belts in equilibrium. Although the total energy of the photoelectron source exceeds 10^9 W, the electrons involved are of relatively low energy (e.g. eV) in comparison to the MeV electrons required to produce the synchrotron emissions. The high efficiency requirement, coupled with the relativistic energy requirement imposed by the microwave spectrum, suggests that a local process operates at or near Jupiter to accelerate the electrons. Electrons to be accelerated could be drawn from the solar wind or from the thermal magnetospheric plasma. If the solar-wind electrons could easily penetrate into the magnetosphere, they would appear to be a likely source, since they are abundant, and could be energized in the transition region between the ambient plasma and the magnetosphere, or in the magnetosphere itself. On the other hand, the acceleration of thermal electrons to high energies is in some ways an attractive hypothesis since the electrons are situated near the belts. A dense, hot model magnetosphere would seem to be most favorable for this process.

There seems to be no shortage of possible acceleration mechanisms. The problem is to find a mechanism which produces a suitable energy spectrum and pitch-angle distribution on a time scale sufficiently fast to replenish the belts as they lose energy. Since there is sufficient power in the solar wind to operate the acceleration mechanism, even at a low efficiency, this power source has been often suggested as the driving force. However, no detailed models for the transfer of energy have been put forward. On the other hand, sufficient kinetic energy is associated with both Io and Jupiter to operate an acceleration mechanism without appreciably altering their periods. These possibilities should be given more consideration.

Chang & Davis (1962) have pointed out that an attractive feature of an acceleration process which operates by conserving the first two invariants of motion, while violating the third, is that it causes particles to diffuse radially inward, gain energy, and attain flat helix orbits. If such a process could be found which worked in the Jovian magnetosphere, it could explain both the high energies and the flat helix orbits which are actually observed. For this reason several authors have considered such a mechanism.

Chang & Davis considered a betatron acceleration process involving transient deformations of Jupiter's magnetic field. They estimate that for any reasonable level of magnetic activity, the time scale for inward diffusion and acceleration of particles is $\sim 10^6$ years, much longer than the lifetime of the electrons against synchrotron radiation. Brice (1968) considered a large-scale electric-field acceleration process, and he too was led to the conclusion that the diffusion time to move electrons radially inward to the belts is too long to make the process workable. Other acceleration processes such as Fermi acceleration, resonant wave particle acceleration, and collisionless shockwave acceleration have received little attention, and their operation time scales are unknown.

INTERACTIONS OF SATELLITES WITH THE MAGNETOSPHERE

At least five of Jupiter's satellites move through its magnetosphere, undoubtedly generating some type of continuous disturbance in the magnetosphere and possibly the ionosphere. This circumstance has attracted much attention since the surprising discovery of the correlation of Io's orbital position with the decametric radio emissions.

Many types of interactions could take place between the satellites and the magnetosphere. These depend not only on the properties of the magnetosphere but also on the electrical and magnetic properties of the satellites themselves. If the satellites are highly permeable and have a magnetic dipole moment, they would be expected to produce local distortions in Jupiter's dipole field which might trap charged particles (Burns 1967). The low mean density of Io ($2.5 \lesssim \rho \lesssim 4$g cm^{-3}) and its low surface temperature (■ 145° K) are not indicative that this satellite has such a property. High-permeability materials generally have densities between 7 or 8 g cm^{-3}, although a few magnetic materials have lower densities. Nonmagnetic or low-permeability satellites moving through the magnetosphere may lose or gain energy (1) by induction interactions, (2) by collective particle or wave interactions, and (3) by individual particle interactions. In the tenuous domain of the outer magnetosphere, the first two of these interactions are likely to produce the largest disturbance, while individual particle interactions could be responsible for organizing the medium into a state favorable for a radiation process to proceed. Field (1966) describes one such effect, that of a satellite sweeping out trapped radiation and creating a barrel-shaped moat in Jupiter's magnetosphere.

Induction interactions.—Whenever a conducting satellite moves through a conducting medium in the presence of a magnetic field which has a component normal to the direction of motion, an electric current is induced in the satellite. The current in turn interacts with the magnetic field to produce a force on the satellite, and deforms the external field. The deformation of the field near the satellite will propagate away as a set of hydromagnetic waves. This type of interaction is called an induction interaction.

One feature of the induction interaction, the ability of the satellite to produce strong deformations of the field, can be understood by considering the time scale on which the magnetic field permeates the satellite. The characteristic time for the magnetic field to diffuse a distance L, where L is a characteristic dimension of the satellite (e.g. the diameter), is given by $t_m \approx \mu\sigma L^2$ where μ is the permeability and σ is the mean conductivity of the satellite. A corresponding diffusion velocity can be defined as

$$V_D = \frac{L}{t_m} = (\mu\sigma L)^{-1} \tag{11.}$$

If the satellite velocity V_s is much less than the diffusion velocity, the magnetic field will diffuse freely through the satellite, causing only minor disturbances to the magnetic field. If, on the other hand, the diffusion velocity is much less than the satellite velocity, then the magnetic field will tend to pile up in the satellite, with the result that the disturbance is transmitted to the surrounding medium. The effectiveness of a satellite in creating an external magnetic disturbance thus depends on the conductivity, permeability, and size of the satellite (Gold 1966, Piddington 1967).

We can estimate the mean conductivity that Io would need for its diffusion velocity to equal its motional velocity. Relative to the corotating plasma, Io moves with a velocity of 5.6×10^4 m/sec. Taking $L = 3.2 \times 10^6$ m for Io's diameter and assuming its permeability is that of free space (i.e. $\mu = \mu_0 = 4\pi \times 10^{-7}$ weber amp^{-1}m^{-1}), we have

$$(\mu\sigma L)^{-1} = 5.6 \times 10^4 \text{ m/sec}$$

from which it follows that $\sigma \approx 6 \times 10^{-6}$ ohm^{-1} m^{-1}. The corresponding characteristic time of diffusion is $\sim$1 min. For values of the conductivity $> 6 \times 10^{-6}$ ohm^{-1} m^{-1}, the magnetic field can be considered to be frozen out of or into the satellite. If the magnetic field has not yet permeated the satellite, and its conductivity is sufficiently high, then the lines of force are forced to pile up as a result of Io's motion. How this disturbance propagates away depends on the ratio of the satellite velocity to the hydromagnetic wave velocity in the magnetosphere.

Piddington (1967) has suggested that the long immersion of Io in the main steady field of Jupiter must insure its magnetization. For this case, the magnetic-field lines are frozen into the satellite if the conductivity is sufficiently high. Piddington (1967), Piddington & Drake (1968), and Goldreich & Lynden-Bell (1969) have discussed in considerable detail the consequences of having the field lines frozen into Io. The main consequence is that the plasma contained in the flux tube which passes through Io will move as though it were rigidly attached to the satellite. The two feet of the flux tube will be forced to "slip" relative to the corotating atmosphere.

Wave interactions.—This second type of interaction has not been studied as extensively as the first. The requirement is that the satellite be capable of exciting a wave-type disturbance (by means other than induction) in the magnetosphere which may draw on the kinetic energy of the satellite. One type of possible interaction assumes that the satellite is charged, and that the motion of this charged body through the magnetosphere stimulates waves in the surrounding medium. The simplest purely sinusoidal disturbances which propagate in the plasma may be classified under three categories: radio-frequency electromagnetic waves, low-frequency magnetohydrodynamic waves, and electrostatic waves.

For radio-frequency electromagnetic waves in the presence of a uniform magnetic field, the phase velocity v_ω is given by

$$\frac{v_\omega^2}{c^2} = \frac{\omega(\omega \pm \omega_g \cos\theta)}{\omega^2 - \omega\omega_g \cos\theta - \omega_p^2} \qquad 12.$$

where c is the velocity of light, $\omega_g = eB/m$ is the electron cyclotron frequency, $\omega_p = (4\pi N_e^2/\epsilon_0 m)^{\frac{1}{2}}$ is the electron plasma frequency, and θ is the angle between the wave normal and the magnetic-field vector. Ellis (1965) points out that since the phase velocity tends to zero in the direction given by $\omega = \omega_g \cos\theta$, the velocity of Io will exceed the velocity of phase propagation for all wave frequencies less than the electron cyclotron frequency, and the satellite will continuously excite Cerenkov shock waves in the surrounding medium.

The simplest low-frequency (lower than the ion cyclotron frequency) waves are the transverse Alfvên waves, which can propagate at an angle θ with respect to the magnetic field with a velocity $v_A \cos\theta$, where $v_A = H/\sqrt{4\pi\rho}$. These waves are excited by an initial displacement of the material in a direction perpendicular to $\overline{H}$. Estimates of v_A in the vicinity of Io range from as low as 700 km sec^{-1} (Ellis 1965) to 10^5 km sec^{-1} (Warwick 1967). The motion of Io is so very much slower that strong shocks in its vicinity seem unlikely unless they take place for waves propagating nearly normal to the field (Ellis 1965). The possibility that Alfvên waves generated close to Io may eventually steepen into shocks as they approach the planet has been mentioned by Warwick (1967) and Marshall & Libby (1967).

The third type of waves which may be induced are electrostatic waves or plasma oscillations. In these waves, an electrostatic field produced by charge separation provides a restoring force which causes the medium to oscillate with an angular frequency given by ω_p. Gledhill (1967a) has mentioned that Io may directly stimulate plasma waves although the interaction is not discussed.

Decameter Emission Theories

Prior to the discovery of the Io correlation, a number of theories were proposed to explain the origin of the decameter radio emissions. The majority attributed the low-frequency radiation to an emission process occurring at or near the electron gyrofrequency or the plasma frequency. Reviews of these theories have been given elsewhere (e.g. Warwick 1967, Ellis 1965, and Warwick 1964).

Recent theoretical work on this problem has centered around the question of how Io modulates the emission. Gledhill (1967a), Burns (1967), Piddington & Drake (1968), and Goldreich & Lynden-Bell (1969) have advanced new theories to explain the Io effect, while Ellis (1965) and Warwick (1967) have both updated their early theories. Io control is introduced into the Doppler-shifted cyclotron theory of Ellis & McCulloch (1963) by requiring that Io generate hydromagnetic or electromagnetic radiation, and that the radiation propagate through the large difference in Jupiter longitude between the position of Io and the source region of the decameter radiation. Warwick believes that hydromagnetic waves or particle disturbances generated near Io must cross from an L shell of 6 to a smaller L shell value in order to generate emission beamed towards the Earth. The theory of Burns has already been mentioned in the section on satellite interactions, while the suggestions of Piddington & Drake have been incorporated into the Goldreich & Lynden-Bell theory and will not be discussed individually.

Gledhill model.—Gledhill (1967a) assumes that Io generates waves locally, at or near the plasma frequency by the passage of Io through the ambient plasma. He asserts that the plasma frequency in the vicinity of Io rises to, but does not exceed that corresponding to the plasma density given by Equation 9. An objection to this theory is that there is no apparent source for the high densities required by the model. The density at Io's orbit is required to be as large as or larger than that estimated for the ionosphere itself, while the gravitational potential barrier tends to prevent the ionosphere from being a good source of ionization unless its temperature is very high. If indeed the density in the magnetosphere does vary like r^{-8} as Gledhill suggests, the work of Melrose (1967) would indicate that the distribution is unstable. Melrose finds that the magnetosphere becomes unstable against interchange motions if the density falls off faster than r^{-4}.

Theoretical work of Goldreich & Lynden-Bell.—The most complete model to date of the interaction between the satellite Io and the Jovian magnetic field is that of Goldreich & Lynden-Bell (1969). They assume that Jupiter is successively enclosed by a corotating electrically insulating atmosphere, an ionosphere, and a low-density ($.1-10$ cm^{-3}) collisionless magnetosphere which extends beyond Io's orbit. Io itself is assumed to be magnetically inert but has a conductivity which is possibly similar to that found in the Earth's upper mantle. The main steady component of Jupiter's magnetic field is assumed to have permeated Io because of its long immersion in the field. As a first approximation it is assumed that in a frame of reference moving with Io, the electric field in the satellite vanishes. It turns out to be important for the theory that the conductivity be $>2\times10^{-6}$ ohm^{-1} m^{-1}. A consequence of this assumption is that a free surface charge density forms on Io's surface, creating an electric field which just cancels the corotational electric field. Perfect conductivity along the field lines outside of Io implies that the electric field must vanish everywhere within the tube of magnetic flux which passes through the satellite. The plasma contained within this flux tube will then move as though it were rigidly attached to the satellite. Piddington & Drake (1968) were the first to point out that Io's flux tube may be frozen to the satellite. The two feet of the flux tube (in the northern and southern magnetic hemispheres) are forced to slip relative to Jupiter's corotating ionosphere. As seen in a reference frame rotating with the planet, there is induced voltage across Io of $\sim 6.7 \times 10^5$ V which causes a current to be driven through the ionosphere. The current flows down from the satellite along one half of the surface of the flux tube, crosses the flux tube in the ionosphere and then flows back up to the satellite along the opposite half of the flux-tube surface. The total current flowing along the flux tube is $\sim 1.1 \times 10^6$ amp while the power dissipated in the ionosphere at each foot of the flux tube is 5.8×10^{11} W.

The available power in the kinetic energy of the electrons which stream along Io's flux tube is $\sim 4 \times 10^{10}$ W while an individual electron has a kinetic energy of ~ 2.5 kV. Goldreich & Lynden-Bell argue on the basis of the beaming of the low-frequency bursts that coherent cyclotron radiation produced by these current-carrying electrons is responsible for the decametric radiation. They suggest that the instability responsible for the Jovian decametric emissions occurs for radiation propagating nearly at right angles to the magnetic-field lines and may be associated with the relativistic mass change of the radiating electrons. In this process, those electrons which have initial phases such as to gain energy from an electromagnetic wave propagating in the medium become more massive and tend to accumulate phase lag; those with initial phases such as to lose energy to the wave, become lighter and accumulate phase lead. The resulting bunching then brings about coherent emission. The assumed amplification process requires a distribution of electron momenta which is populated more heavily at higher values than at lower ones over a particular momentum range. For the weakly relativistic electrons which carry the current along the flux tube which passes through Io, amplification occurs primarily near the fundamental electron cyclotron frequency.

Goldreich & Lynden-Bell explain the negative frequency drifts of the *S* bursts as being produced by radiating electron bunches which flow up to Io from the feet of the flux tube. The negative drift rate is then interpreted to be the rate of change of the local gyrofrequency for the bunch of electrons. They find that the radiation is confined to a conical sheet which opens at an angle of nearly 79° from the magnetic-field direction, a similar conclusion having been reached by Dulk (1965) on geometrical grounds. Although the highly asymmetrical longitude dependence of the bursts is not explained by this theory, the agreement between the beaming angle predicted by the theory and that found from observation, as well as the logical origin of the conical beaming, makes this an extremely attractive theory.

CONCLUSIONS

Although it has been possible to derive considerable information about Jupiter's magnetic field and its radiation belt from observations of its decimetric radio emissions, there are still wide gaps in our understanding of the structure and processes which occur in the magnetosphere. As yet no theory explains the origin of the Van Allen belts. The magnetic-field strength in the belts is poorly known. The degree of symmetry of the magnetic field remains an outstanding unknown. Even the derived pitch-angle distribution and energy spectra of the relativistic electrons are very doubtful. High-resolution brightness-distribution observations at a number of frequencies including some below 300 MHz should help to better define these quantities.

Theoretical considerations have shown that the magnetosphere is divided into gravitationally and centrifugally dominated regions, the latter occupying the largest part of the magnetosphere. Opinion as to the density of the thermal plasma in the centrifugal region is widely divergent, and experimental results have been of little value in choosing among the various models.

Finally we mention that there is still no widely accepted theory of the origin of the decameter emissions. One of the more recently proposed theories, that of Goldreich & Lynden-Bell, appears promising. Measurement of the true source positions relative to Jupiter's disk would help to eliminate a number of the many conflicting theories.

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CONTENTS