THE RADIO EMISSIONS FROM JUPITER AND THE DENSITY OF JOVIAN EXOSPHERE

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Summary

The properties of cyclotron radiation from bunches of electrons trapped in a Jovian exosphere are discussed. It is shown that, if the polar magnetic field intensity is 15 gauss and the magnetic axis is inclined 10° to the rotation axis, the calculated properties agree with those observed for the decametric radiation providing Jupiter is surrounded by an extensive exosphere. The electron density of the exosphere varies mainly as the magnetic field intensity and at $1\cdot 5R_{\mathrm{j}}$ is equal to $10^3/\mathrm{cm}^3$.

I. Introduction

Recent investigations of the decametric and decimetric radiations of Jupiter and of the V.L.F. radiations from the Earth's exosphere have suggested that they all arise from the same basic process, namely, acceleration radiation by electrons travelling along helical paths in magnetic fields. In the case of the Earth, the observed properties of the terrestrial emissions are explained in considerable detail if they are caused by cyclotron radiation by bunches of electrons trapped in the exospheric magnetic field (Dowden 1962*a*). Similarly, the low frequency Jupiter radiation is accounted for by cyclotron radiation by bunches of electrons in a Jovian magnetic field (Ellis 1962), providing it is assumed that Jupiter is surrounded by an extensive ionized exosphere, like that of the Earth.

Two alternative interpretations of the high frequency Jupiter radiation have been put forward. Field (1960) has suggested that its source is cyclotron radiation by non-relativistic electrons in a very strong magnetic field, of the order of 1000 gauss at the poles. However, more recent observations at 1400 Mc/s by J. A. Roberts (personal communication) are simply explained on the assumption that they result from synchrotron radiation by relativistic electrons in a much weaker field. Roberts' results indicate a field with a polar intensity of $\sim$15 gauss inclined $\sim$10° to the rotation axis of Jupiter. In addition, he finds the north magnetic pole to be in longitude 185° (System III).

Credence is lent to these general ideas by the independent observation that a magnetic pole longitude of 190° (System III) is deduced from the variation of the low frequency radiation, interpreted as cyclotron radiation (Ellis and McCulloch 1962).

Here we are concerned mainly with the properties of the low frequency radiation. These are almost independent of the magnitude of the magnetic field and cannot therefore provide much information about it. However, if the magnetic field can be

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estimated, as for example from the 1400 Mc/s results of Roberts, then the study of the low frequency radiation can give detailed information about the ionized exosphere of Jupiter.

Previously the radiation and exospheric properties expected with a polar field of 1000 gauss have been analysed (Ellis 1962). Here we consider a 15 gauss field.

II. Theory

The wave frequencies of the electromagnetic radiation from a single relativistic electron travelling along a helix in a magnetic field H and plasma of density N are given by the generalized Doppler equation

$$f_s = \frac{s\gamma f_H}{1-(v_2/c)n\cos\theta}, \tag{1}$$

where v_2 is the velocity in the direction of the magnetic field,

θ is the direction of the wave normal with respect to the magnetic field,

$\gamma = \sqrt{(1-v^2/c^2)}$,

$f_H = eH/2\pi mc =$ cyclotron frequency,

$s = 0, 1, 2, 3,$ etc.,

e, v, and m are the charge, velocity, and rest mass of the electron,

n is the Appleton-Hartree refractive index of the plasma.

Equation (1) must be solved simultaneously with that for the refractive index to obtain possible values of f_s and θ. The energy radiated may then be calculated using the classical radiation equations (Eidman 1958; Ellis 1962). Since the refractive index equation is complicated it is convenient to solve (1) graphically by rewriting it as a function of n, that is,

$$n = (1-s\gamma f_H/f_s)\{(v_2/c)\cos\theta\}^{-1}, \tag{2}$$

where for a plasma

$$n = n(H, f, \theta, N). \tag{3}$$

For weakly relativistic electrons we need only consider the fundamental frequencies of radiation, that is, we take $s = 1$.

In general, in the forward direction, that is, $0<\theta<\frac{1}{2}\pi$, solutions exist only if θ is less than some limiting value θ_{m}. The radiation is thus confined to a cone about the magnetic field direction, unlike the case of cyclotron radiation in a vacuum where there are no forbidden directions. Simple considerations provide important information about the properties of the radiation in a planetary magnetic field and exosphere such as is envisaged for Jupiter. The final limiting direction of propagation of the radiation will not then be given by θ_{m} since the emission occurs in a medium of refractive index n. However, the subsequent refraction can be calculated using Snell's law without significant error by assuming that surfaces of equal refractive index are plane and parallel in the region of greatest refraction. They will be normal to the magnetic field vector since it is assumed that the electron density is proportional to the magnetic field intensity.

If, then, the angle θ_{mr} between the final limiting direction of propagation and the field vector at the point of emission of a wave of frequency f is less than the angle ϕ between the field vector and the plane of the magnetic equator, no radiation will be visible at this frequency in this plane.

If the magnetic dipole axis is inclined to the rotation axis of Jupiter at angle α and if the Earth is in the plane of the rotation equator then the radiation may be observed to diminish to zero twice during each rotation. If

$$\theta_{mr} < \phi - \alpha,$$

then no radiation would be observable at the Earth at any time.

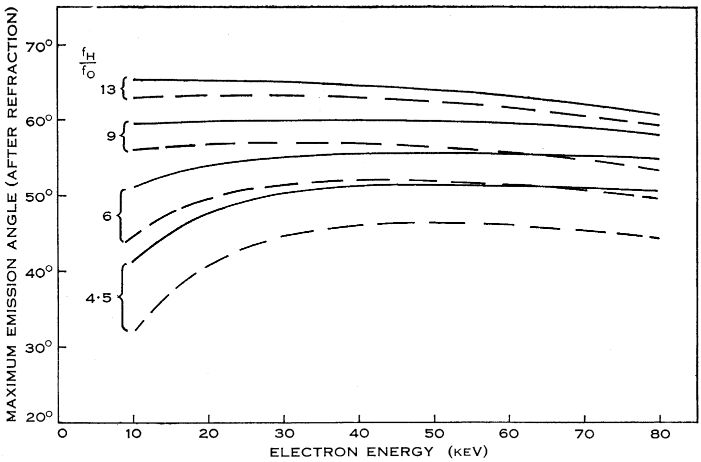

Fig. 1.—Variation of the angular size of the emission cone, θ_{mr}, with electron energy for different values of the plasma frequency; $f_H = 4 \cdot 5$ Mc/s. Solid lines, electron pitch angle zero; dotted lines, pitch angle 30°.

The magnitude of θ_{mr} is strongly dependent on the ratio between plasma frequency f_0 and the cyclotron frequency f_H at the point of emission. However, it is surprisingly independent of the velocity of the electrons. Figure 1 shows that θ_{mr} remains almost constant for electron energies between 30 and 80 keV, with different values of f_H/f_0. If ϕ and α are known, the wave frequency limits, beyond which the radiation is unobservable, may be used to establish the ratio at the corresponding emission levels and hence f_0 and the plasma density N, since f_H will be determined. In addition, comparison of the observed rotation at intermediate wave frequencies with the computed variation enables the density to be estimated at intermediate levels. In regions where the density varies as the magnetic field intensity only one of these measurements is necessary to establish the density everywhere.

III. Discussion

(a) *Magnetic Field of Jupiter*

We consider here a Jupiter magnetic field with a polar intensity of 15 gauss and with the dipole axis inclined 10° to the rotation axis. We assume also that the bunches of electrons producing the radiation travel only along the field lines which pass near the outer boundary of the magnetic field. This limitation is suggested from experience with the terrestrial very low frequency emissions. Here the pressure of solar streams limits the geomagnetic field during magnetic storms to a radial extent of $5 \cdot 5$ Earth radii on the day side (Martyn 1951), while the field lines along which most of the discrete VLF emissions originate have a normal radial distance of $3 \cdot 5 R_{\mathrm{e}}$ (Dowden 1962*b*).

It seems reasonable to assume that for Jupiter also, the mechanisms leading to acceleration and bunching of electrons are most active near the outer boundary of the field. The actual location of the boundary is more uncertain for Jupiter since nothing is known about the likely properties of solar streams in its neighbourhood. However, in the absence of solar streams the magnetic field will be limited by the rapid rotation of the planet within the surrounding ionized interplanetary medium, and its extent may be estimated by equating the magnetic energy density of the field and the relative kinetic energy density of the medium.

If we take initially the dipole axis to be the same as the rotation axis we have

$$2\pi^2 \rho R^2 / T^2 \cos^2\lambda = H^2/8\pi$$
$$= H_{\mathrm{p}}^2 \, R_{\mathrm{j}}^6 \cos^2\lambda (1+4\tan^2\lambda)/32\pi R^6$$

or

$$R^8 = T^2 \, H_{\mathrm{p}}^2 \, R_{\mathrm{j}}^6 \, (\cos^4\lambda + \sin^2 2\lambda)/64\pi^3 \rho, \tag{4}$$

where H_{p} = polar magnetic field intensity,
ρ = mass density of interplanetary medium,
λ = magnetic latitude,
T = rotation period.

Since R varies as the one-fourth power of the polar field intensity and inversely as the one-eighth power of the mass density, it can be determined quite closely, even if these parameters are somewhat uncertain. With $T = 35700$ s, $H = 15$ gauss, and one proton/cm^3 in interplanetary space, $R = 33 R_{\mathrm{j}}$ in the equatorial plane.

If the dipole axis is inclined to the rotation axis a small amount, as assumed here, the form of the boundary will be more complicated than equation (4) but its radius for $\lambda = 0$ will be almost as calculated. This value may be regarded as an absolute upper limit and in the presence of energetic interplanetary particle streams is likely to be somewhat less, especially on the day side. In any case it appears that the field lines passing close to the boundary in the equatorial plane may intersect the planet at latitudes of 75° or higher.

In calculating the properties of the radiation the important field parameters are the polar intensity, the direction of the dipole axis, and the inclination of the field line near the planet. For field lines ending at high latitudes the last parameter in particular varies only slightly with large changes in the equatorial radii of the lines and we assume here for the purposes of illustration that the radiating electrons travel along lines extending outwards $17 R_{\mathrm{j}}$. The results may be considered typical of values from $15 R_{\mathrm{j}}$ to $25 R_{\mathrm{j}}$.

(*b*) *Radiation Properties*

We assume that the radiation received at the Earth comes from bunches of electrons that can occur with equal probability in all magnetic longitudes. Using the above model the computed variation in its intensity with Jupiter longitude at a

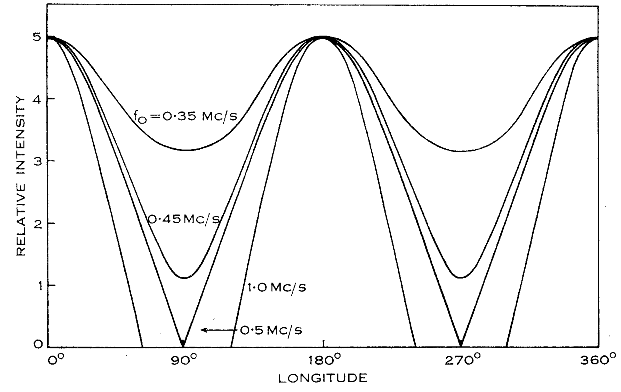

Fig. 2.—Variation of the average intensity of the Jupiter radiation at 4·8 Mc/s, with longitude and with different values of the plasma frequency. $f_H = 4 \cdot 5$ Mc/s, inclination of dipole axis 10°, polar field intensity 15 gauss, electron energy 30 keV, pitch angle zero, latitude of field line 75° at planet.

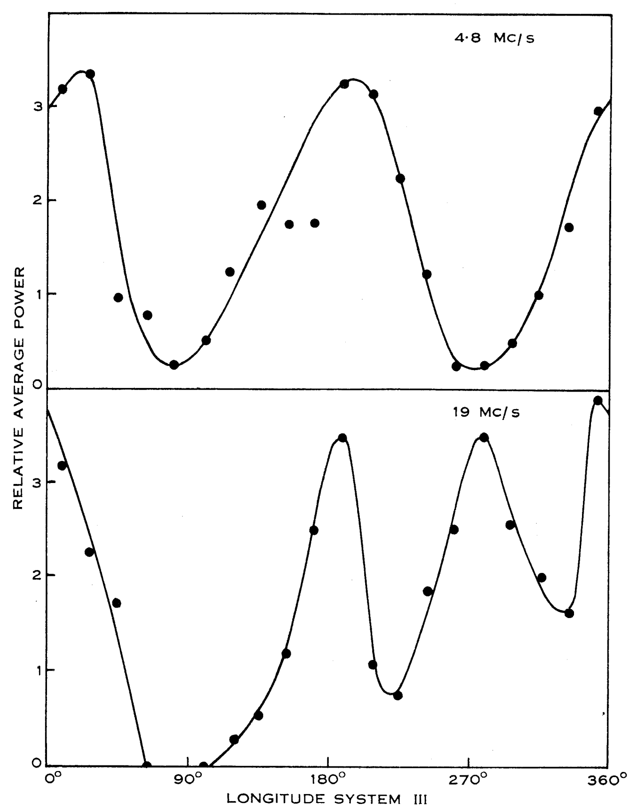

Fig. 3.—Observed variation in the average intensity of the Jupiter radiation at 4·8 and 19 Mc/s.

frequency of 4·8 Mc/s is shown in Figure 2 for different values of the parameter f_0. It can be seen that the shape of the profiles is strongly dependent on this parameter. Comparison of these curves with the observed variation at 4·8 Mc/s (Fig. 3) suggests that for this model a suitable value of the plasma frequency f_0 would be 0·45 Mc/s at the point where the cyclotron frequency f_H is 4·5 Mc/s. If the electron density varies as the magnetic field intensity then the expected variation of the radiation with rotation can be computed for other frequencies if it is known at one frequency. Figure 4 shows two such profiles, one at 4·8 Mc/s and the other at 1·2 Mc/s.

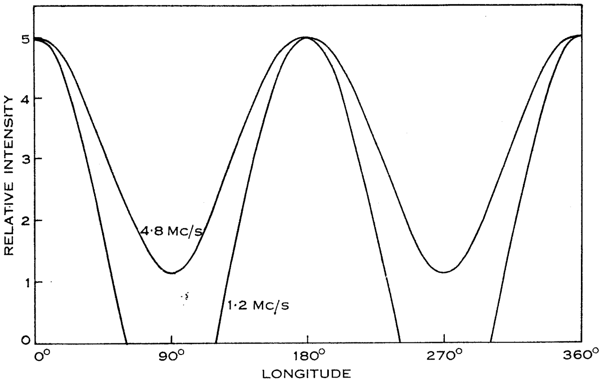

Fig. 4.—Comparison of the variation at 4·8 and 1·2 Mc/s if the plasma density varies as the magnetic field intensity. Other parameters as in Figure 2 with $f_0 = 0{\cdot}45$ Mc/s at the $f_H = 4{\cdot}5$ Mc/s level.

The limits of the frequency range determined by the geometrical consideration $\theta_{\mathrm{mr}} < \phi - \alpha$ discussed earlier, may be calculated for a given electron density model. With a plasma frequency of 0·45 Mc/s at a cyclotron frequency level of 4·5 Mc/s on a latitude = 75° field line, θ_{mr} and ϕ remain almost equal over a considerable range of frequencies. Figure 5 shows that θ_{mr} becomes less than $\phi - \alpha$ with $\alpha = 10°$ only for wave frequencies less than 0·7 Mc/s and hence this would be the low frequency limit for the Jupiter radiation on this model. At higher frequencies than 10 Mc/s, $\theta_{\mathrm{mr}} - \phi$ remains almost constant and no limit appears.

However, it is observed that between 20 and 30 Mc/s the radiation becomes increasingly difficult to detect and also shows anomalous variation in its rate of occurrence and intensity with planetary rotation at frequencies above 15 Mc/s (Smith and Carr 1959; Ellis and McCulloch 1962). Figure 3 shows that, compared with 4·8 Mc/s, there is an additional peak in the rotational variation at 19·0 Mc/s near longitude 270°, System III. In addition, the minimum near longitudes 90° is deeper. On the present theory the deeper minimum and the cut-off at higher frequencies may be accounted for if the exospheric density varies more strongly than as the magnetic field intensity at heights below the 15 Mc/s cyclotron frequency level. Figure 6 shows the density profile calculated from the observations at 4·8 Mc/s, 19 Mc/s, and an assumed upper frequency limit of 28 Mc/s. It can be seen that a rapid increase in the density is necessary in the lower part of the exosphere. This behaviour is familiar in the case of the Earth, where it is due to the transition from the magnetic control of density in the exospheric region to gravitational control of the upper ionosphere.

The actual height at which the calculated transition occurs for Jupiter depends very much on the initial assumptions. With a polar field intensity of 11 gauss,

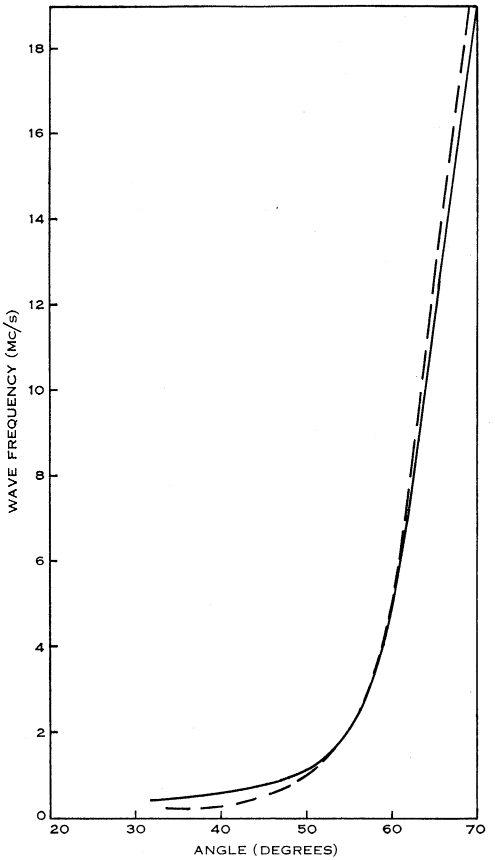

Fig. 5.—Variation of the field line inclination ϕ (dotted line) and the angular size of the emission cone θ_{mr} (solid line) with wave frequency; parameters as in Figures 2 and 4.

for example, instead of 15 gauss it would be 1000 km instead of 10 000 km. It is noteworthy that different assumptions of the value of the polar field and electron energy do not greatly affect the density calculated for the level in the exosphere corresponding to the observed wave frequency. The previous analysis with a 1000 gauss field and 15 keV electrons (Ellis 1962) indicated a plasma frequency of 0·45 Mc/s at the $f_H = 4\cdot 8$ Mc/s level, almost the same as obtained here. However, the height at which it occurred was very much greater ($8R$ compared with $2R$).

The anomalous peak in the rotational variation for frequencies above 15 Mc/s shown in Figure 3 may be explained on the present theory in terms of a corresponding magnetic anomaly in the field distribution. On the above model a change in the inclination of the magnetic vector of 10° with respect to that of a dipole in the vicinity of the 75° latitudes and over a longitude range of about 80° would be sufficient to produce the observed results. More detailed observations at the higher frequencies are necessary in order to study this anomaly and also to provide further

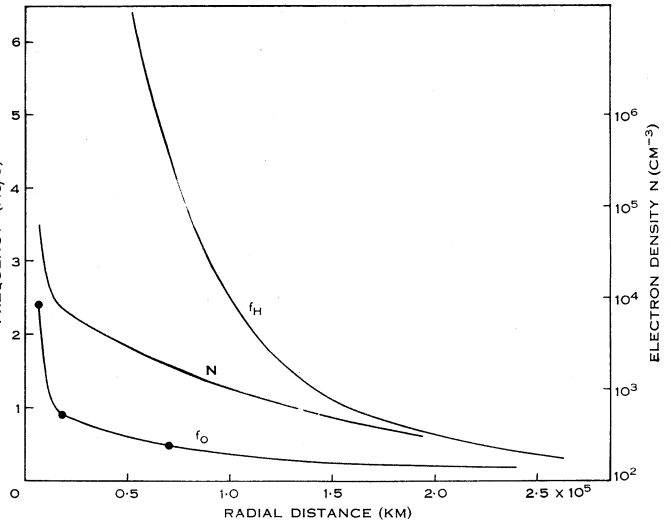

Fig. 6.—Computed variation of the plasma density with radial distance near latitude 75°.

information about the variation of the exospheric density with height. In addition, spectrum analysis of the radiation at frequencies below 15 Mc/s might be expected to throw some light on the dynamic properties of the electrons.

IV. References

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