The Source of Radiation from Jupiter at Decimeter Wavelengths

GEORGE B. FIELD*

Princeton University Observatory
Princeton, New Jersey

Abstract—The flux of radiation from Jupiter at decimeter wavelengths is relatively large, and is approximately independent of wavelength in the interval from 3 cm to 68 cm. Four possible sources of this radiation are proposed and discussed quantitatively. It is concluded that the radiation does not originate in Jupiter's ionosphere, nor does it seem likely that it comes from its atmosphere. It is not due to synchrotron radiation by cosmic-ray electrons. On the other hand, electrons from the sun which are trapped in Jupiter's magnetic field may very well be the source. Observations for testing whether this possibility is correct are discussed.

INTRODUCTION

Recent data (Table 1) indicate that the emission by Jupiter at decimeter wavelengths is unexpectedly large. The disk temperature at 3-cm wavelength is only slightly higher than the infrared value of 130øK [Menzel, Coblentz, and Lampland, 1926]. At longer wavelengths the temperature rises rapidly, and the flux may be the more appropriate parameter; it is given by \(2k\Omega(T_d/\lambda^2)\), where \(\Omega\) is the angular disk. With the exception of the 3-cm results, we may summarize Table 1 by taking the flux (in units \(2k\Omega\)) to be approximately constant at \(10^7\text{K cm}^{-2}\).

Such a variation of flux with wavelength is of course inconsistent with black-body emission by the surface of the planet. At least four possible sources that might account for the spectrum can be imagined: (1) thermal emission by a deep atmosphere with a temperature gradient, whose opacity depends on wavelength; (2) free-free emission by an ionosphere; (3) a cloud of non-relativistic electrons emitting the cyclotron frequency at various points in Jupiter's magnetic field, and (4) a cloud of relativistic electrons emitting harmonics of the cyclotron frequency. In the next four sections we shall examine each of these possibilities, concluding with a discussion of observational tests. In the remainder of the present section, we shall consider information on Jupiter's atmosphere and ionosphere which is important in the later discussion.

The information about the atmosphere has been summarized by Kuiper [1952]. He proposes a model in which a stratosphere of constant temperature 86øK extends down to a convective region having the adiabatic temperature gradient. The visible clouds are at a level where the temperature is 168øK. One sees absorptions due to ammonia and methane above these clouds, in amounts equivalent to 700 cm and 15,000 cm, respectively, at NTP. Molecular hydrogen is also seen in absorption [Kiess, Cor-
iss, and Kiess, 1959], but as yet there are no quantitative estimates of its abundance based on the absorption features, although Kuiper implies that, if the cosmic abundance of hydrogen obtained, the hydrogen lines would be stronger than observed. Helium is doubtless present—20 per cent by mass if the composition is similar to that of the primeval sun [Schwarzchild, Howard, and Härm, 1957]. Herzberg [1952], in studying the hydrogen lines in Uranus, noted the absence of a line due to a collision-induced double transition in which both collision partners share—a line that is strong in the laboratory. He concluded that most collisions must therefore be with foreign atoms (presumably helium) in Uranus. From the weakening of the line he estimates that the helium-hydrogen ratio is 3 to 1 by number. Preliminary indications are that the same line is missing in Jupiter, which again suggests a rather high helium abundance.

Baum and Code [1953] deduced a mean molecular weight of 3.3 for the Jovian stratosphere from observations of an occultation by Jupiter. This corresponds to 79 per cent helium by mass if the remainder is hydrogen. Although there was considerable uncertainty, we have here another argument for high helium content. We shall therefore assume that Kuiper’s ‘model b’ for a helium-rich atmosphere gives a good description of relative abundances. This model has 37.7 per cent hydrogen molecules, 59.5 per cent helium, and 2.8 per cent of other gases including neon, water, methane, and ammonia. The mean molecular weight comes out to be 3.26, in good agreement with Baum and Code’s determination. The mean ratio of specific heats, \( \gamma \), is 1.56.

Particularly important to us is the abundance of ammonia, since it supplies most of the radio-frequency opacity. Its relative abundance by number, \( a_\alpha \), based on cosmic abundance ratios, is \( 5.8 \times 10^{-3} \) for the helium-rich atmosphere (as against \( 3.7 \times 10^{-4} \) for a hydrogen-rich atmosphere). The amount of ammonia should somewhat exceed the amount of methane, according to Kuiper; the low ratio of the observed amount of ammonia to the observed amount of methane (4.7 per cent) Kuiper attributes to the low vapor pressure of ammonia in the cold upper parts of the convective layer—natural enough if the clouds are believed to be solid ammonia crystals. Certainly Kuiper’s picture receives strong support from the fact that it predicts that the level at which infrared saturation takes place has a temperature of 130°K, in agreement with observation.

Turning now to the ionosphere, we shall rely on information provided by the low-frequency bursts from Jupiter and by the ionizing power of solar radiation. Bursts are often observed at a frequency of 18 Mc/s [Carr, Smith, Pepple, and Barrow, 1958]. These bursts seem to originate in a small area and thus allow a determination of the Jovian period of rotation. That the period has remained quite constant over a 5-yr interval may be taken as evidence that at least the primary source of the bursts is rotating rather rigidly. It therefore seems unlikely that this source is at a great altitude above the planet, in particular, above its ionosphere. Now, for an 18 Mc/s burst to penetrate the ionosphere, the critical frequency for at least one magneto-ionic mode must exceed 18 Mc/s. There are two cases to consider, depending on the value of the cyclotron frequency, \( \nu_H \) (as \( 2.8H \) Mc/s, with \( H \) the local magnetic field strength). If \( \nu \) (18 Mc/s) exceeds \( \nu_H \) (or \( H < 6.4 \) gauss), the lowest critical frequency (for the ordinary mode) is just the plasma frequency, \( \nu_p = 10^{-\alpha \nu} \) Mc/s, where \( \nu \) is the maximum electron density in the ionosphere. If, on the other hand, \( H > 6.4 \) gauss, the extraordinary mode penetrates at the lowest frequency, namely \( \nu = \nu_p - \nu_H/2 \). We may conclude, then, that \( \nu \) exceeds at least one of these frequencies. In either case we obtain an upper limit on \( \nu \).

\[
\begin{align*}
\text{if } H < 6.4 \text{ gauss} & : \quad \nu_e < \nu \\
\text{if } H > 6.4 \text{ gauss} & : \quad \nu_e < (1 + \nu_H/\nu)^4
\end{align*}
\]

If \( H > 6.4 \) gauss, \( \nu_e < (1 + \nu_H/\nu)^4 \) or, with sufficient accuracy, \( \nu_e < \) larger of \( \nu \) and \( (\nu H)^{1/4} \). Put in terms of electron density, \( n_e < 3.2 \times 10^9 \) cm\(^{-3} \) or 5.0 \( \times 10^5 \) \( H \) cm\(^{-3} \) whichever is larger.

Franklin and Burke [1958] have reported right-hand circular polarization for a number of bursts. They state that this may be explained by assuming that only one magneto-ionic mode is being propagated, the other being below cutoff. Assuming that \( H < 6.4 \) gauss leads to the
conclusion that \( \nu < (\nu_e^2 + \nu_n^2/4)^{1/2} + \nu_n/2 \), the cutoff for the extraordinary mode in the weak-field case. Putting in their frequency (22.2 Mc/s), we have

\[
\nu_n > 22.2 - \nu_n^2/22.2 \tag{2}
\]

and hence a lower limit on \( H \) if \( \nu_0 \) at the moment of observation is known. They point out that suggested techniques for determining \( \nu_0 \) on the basis of escape cones of the observed radiation lead to poor results. It appears that the only safe way is to observe the same burst for polarization on two frequencies; then an upper limit on \( \nu_0 \) follows from equation 1 and a lower limit on \( \nu_n \) from equation 2. As it does not appear that this has yet been done, for the present we must consider both cases: a weak field (< 6.4 gauss) and a strong one (> 6.4 gauss). We shall find, however, that the upper limits provided above are still enough to rule out the ionosphere as the source of the decimeter-wavelength radiation.

**Thermal Emission by the Atmosphere**

If the radiation at 68-cm wavelength is to be explained by a hot atmosphere, it must originate at a point where the atmospheric temperature is 70,000°K. Evidently the most favorable assumption is an adiabatic temperature gradient, since this cannot be much exceeded in any event. The adiabatic gradient of Kuiper's model atmosphere is

\[
\beta = \gamma - \frac{1}{\gamma} \frac{\mu g}{R} = 4.0°K \text{ km}^{-1} \tag{3}
\]

Thus the depth of the 70,000°K zone must be some 17,500 km; the pressure there approaches 1.8 \times 10^8 atmospheres, and the density, 100 g cm^{-3} (assuming the perfect gas law). Ramsey [1951] has pointed out that 8 \times 10^8 atmospheres is the critical pressure for the transition of molecular hydrogen to metallic hydrogen at zero absolute temperature. Although it is not clear how the high temperatures and helium dilution will modify this result, we can be sure that the equation of state will be profoundly affected by such high densities, with the intermolecular distance only 0.4 Å.

Is it conceivable, in fact, that the atmosphere will be transparent down to anywhere near the 70,000°K level? The answer to this question is 'yes'; it depends on the fact that neither hydrogen nor helium has dipole moments, and hence they are poor absorbers in the radio-frequency range. It is likely that the dominant source of opacity is ammonia, which has the well-known inversion spectrum near 1.25-cm wavelength. But ammonia is much reduced in abundance, and so it turns out that the opacity is quite moderate.

To summarize: we assume an adiabatic atmosphere of temperature gradient 4°K km^{-1}, whose composition includes 5.8 \times 10^{-3} ammonia molecule to every one of another kind. We shall assume that the perfect gas laws hold, in spite of the high pressures, and that ammonia is the only absorber. Obviously these assumptions are most advantageous to the present hypothesis, since smaller gradients or other absorbers (such as those due to ionization) would make it harder to receive radiation from the hotter layers.

The absorption coefficient of ammonia [Townes and Schawlow, 1955] depends on the frequency through the Van Vleck-Weisskopf formula:

\[
\kappa = \frac{8\pi^2\nu^2 n(NH_3)}{3kT} \sum_i f_i |\mu_{ij}|^2 \left\{ \frac{\Delta \nu_{ij}}{(\nu - \nu_{ij})^2 + (\Delta \nu_{ij})^2} \right\} \tag{4}
\]

In this equation \( i \) and \( j \) are two rotational fine-structure levels of the inversion line; \( \nu_{ij} \) is the precise frequency of the transition \( i \rightarrow j \) (near 0.8 cm^{-1}), \( \Delta \nu_{ij} \) is the collision frequency appropriate for the \( i \rightarrow j \) transition, and \( \mu_{ij} \) is the corresponding dipole moment matrix element. All frequencies are in cm^{-1}, \( f_i \) is the fraction of molecules in the \( i \)th level. Since at high temperatures many levels are populated, the precise evaluation of the sum becomes quite complex. But it may be readily simplified by assuming that \( \nu \ll \nu_0 = \langle \nu_{ij} \rangle \), as it will be for our application, since \( \nu_0 \approx 1.25 \text{ cm} \). Furthermore, we may take \( \Delta \nu_{ij} \) to be relatively independent of \( i \) and \( j \), so the sum is replaced by

\[
\frac{2\Delta \nu}{\nu_0^2 + (\Delta \nu)^2} \sum_i f_i |\mu_{ij}|^2 \tag{5}
\]

Swarup [1954] has estimated that at NTP the
sum in this equation is about 0.4 \mu_0^2, with \mu_0 = 1.47 \times 10^{-18} \text{ egs.} \ We shall assume the same relation to hold even at our much different temperatures.

Bleaney and Loubser [1950] have shown that, whereas equation 5 holds at low pressure with \Delta \nu \propto \nu_0 two effects take place: \nu_0 approaches zero, and \Delta \nu/p assumes a smaller value. Their work was concerned with pure ammonia, but it seems likely that similar effects will occur in a hydrogen-helium mixture, as the effects are in accord with a theory applying to any type of collision. We find (using the collision parameters given by Townes and Schawlow [1955, p. 364] for hydrogen and helium) that \Delta \nu/p = 0.048 \text{ cm}^{-1} \text{ atm}^{-1} for our mixture at low pressures, so that the high-pressure effects may be expected at about 17 atmospheres pressure. For higher pressures, the line shape becomes \frac{2\Delta \nu}{\nu_0^2 + \Delta \nu^2} rather than \frac{2\Delta \nu}{\nu_0^2 + \Delta \nu^2}, where \Delta \nu' signifies the collision frequency with the high-pressure coefficient.

In spite of this we shall use the low-pressure profile for all pressures. It certainly will be correct for pressures much less than 17 atmospheres. Right at the critical pressure, the ratio of the correct to the assumed profile is 2\Delta \nu/\Delta \nu', since \nu \ll \nu_0 and \Delta \nu \simeq \nu_0 there. At higher pressures \nu_0 is negligible, and the ratio is of order \Delta \nu/\Delta \nu', which for pure ammonia is about 3. Unfortunately the corresponding ratio for hydrogen and helium is unknown. We shall assume that the ratio is unity so that we may take \frac{2\Delta \nu}{\nu_0^2 + \Delta \nu^2} throughout. Our opacities are therefore probably too small by a factor of 2 or 3. We thus replace equation 4 by

$$
\kappa = \frac{6.4\pi^2 \mu_0^2 \alpha^2}{3} \left( \frac{n}{T_\nu^0 + \Delta \nu^2} \right)
$$

where we have assumed \alpha = n(\text{NH}_3)/n to be independent of depth, and where the factors in parentheses depend on the depth through

$$
T = T_c(n/n_c)^{\gamma - 1}
$$

$$
\Delta \nu = \Delta \nu_c(n/n_c)
$$

c referring to the cloud level. (We ignore a slight \(T\)-dependence of \Delta \nu.)

We may compute the optical depth down to a level where the density is \(n\), if we assume that the atmosphere is adiabatic up to \(n = 0\), from

$$
\tau(n) = \int_{x(0)}^{x(n)} \kappa \, dx = \frac{\beta}{T_\nu(0)} \int_{\tau(0)}^{\tau(n)} \kappa \, dT = \tau_0 \log \left[ \left( \frac{\Delta \nu n}{\nu_0 n_c} \right)^2 + 1 \right]
$$

$$
\tau_0 = \frac{3.2\pi^2 \mu_0^2 \alpha^2 (\gamma - 1) n_c}{3k \Delta \nu \beta} = 1.2 \times 10^6 \frac{\alpha}{\lambda^2}
$$

Evidently \(\tau_0\) is approximately the optical depth down to a level where \Delta \nu = \nu_0, that is, where the pressure is about 17 atmospheres. We note that it varies as \lambda^{-2}, thus opening up the possibility that at sufficiently long wavelengths radiation penetrates from depths having high temperatures. The numerical value of \(\tau_0\) depends only on the temperature gradient and the ammonia abundance, \(n_c/\Delta \nu_c\) being equal to the measured ratio for a hydrogen-helium mixture in the laboratory.

The brightness temperature of a ray making an angle \cos^{-1} \mu with the vertical is

$$
T_B(\mu) = -\int_{\tau = 0}^\infty T(\tau') \, d(e^{-\tau'/\mu})
$$

$$
= -T_c \left( \frac{\nu_0}{\Delta \nu_c} \right)^{\gamma - 1}
$$

$$
\cdot \int_{y = 0}^\infty y^{(\gamma - 1)/2} \, dy = (y + 1)^{-\gamma/\mu},
$$

and the disk temperature is

$$
T_D = 2 \int_0^1 \tau_B(\mu) \, d\mu
$$

Using equations 9 and 10, we computed \( t = T_D/T_c(\nu_0/\Delta \nu_c)^{\gamma - 1} \) for various wavelengths; this was done approximately in the limits \(\tau_0 \gg 1\) and \(\tau_0 \ll 1\), and an intermediate curve was sketched. The results are listed in Table 2 versus \(\lambda/\lambda_c\), where \(\lambda_c\) is a critical wavelength defined by the criterion \(\tau_0(\lambda_c) = (\gamma - 1)/2\); one finds that \(\lambda_c = 2080\alpha^{-4}\) cm. \(t\) is a slowly increasing function of \(\lambda\) for \(\lambda \ll \lambda_c\), but, according to equation 9, approaches infinity at \(\lambda = \lambda_c\), as the integral does not converge there. The physical reason for this result is that increasing \(\lambda\) decreases \(\tau_0\) until, when \(\lambda = \lambda_c\), one sees down to infinitely deep layers. An increase of \(T_D\) roughly proportional to \(\lambda\) is indicated, with slower
increase for small $\lambda$ and faster increase as $\lambda \to \lambda_0$. $\lambda_0$ is 158 cm for Kuiper's abundance of ammonia; the wavelengths for this case are given in the second column of Table 2. In the last column are the predicted disk temperatures on the assumption that $T_\ast = 168^\circ K$ and the pressure is 2 atmospheres at the cloud level. We see at once that these temperatures bear no relation to the observed values at 10.3-, 21.4-, 31-, and 68-cm wavelength. One might hope to improve the agreement by adopting a smaller $\alpha$, which decreases $\tau_0$ and permits penetration at shorter wavelengths. Evidently if we adopt $\alpha = 1.1 \times 10^{-4}$, so that $\lambda_0 = 68$ cm, we find a very high temperature at 68-cm wavelength and somewhat higher temperatures at shorter ones. The new wavelength scale is given by the third column of Table 2; it is still obvious that there is no agreement between theory and observation. The present theory predicts a sharp rise as $\lambda \to \lambda_0$, but the over-all increase is too slow. Nor does it seem possible to improve the agreement by further changes of $\lambda_0$.

TABLE 2—Disk temperatures for a hot atmosphere

<table>
<thead>
<tr>
<th>$\lambda_0$, cm</th>
<th>$T_D$</th>
<th>$T_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha = 5.8$</td>
<td>$\times 10^{-3}$</td>
<td>$\times 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{\lambda}{\lambda_0}$</td>
<td>$T_D$</td>
<td></td>
</tr>
<tr>
<td>0.025</td>
<td>4.0</td>
<td>1.7</td>
</tr>
<tr>
<td>0.05</td>
<td>7.9</td>
<td>3.4</td>
</tr>
<tr>
<td>0.1</td>
<td>15.8</td>
<td>6.8</td>
</tr>
<tr>
<td>0.2</td>
<td>31.6</td>
<td>13.6</td>
</tr>
<tr>
<td>0.3</td>
<td>47.4</td>
<td>20.4</td>
</tr>
<tr>
<td>0.4</td>
<td>63.2</td>
<td>27.2</td>
</tr>
<tr>
<td>0.5</td>
<td>79.0</td>
<td>34.0</td>
</tr>
<tr>
<td>0.6</td>
<td>94.8</td>
<td>40.8</td>
</tr>
<tr>
<td>0.7</td>
<td>110.6</td>
<td>47.6</td>
</tr>
<tr>
<td>0.8</td>
<td>126.4</td>
<td>54.4</td>
</tr>
<tr>
<td>0.9</td>
<td>142.2</td>
<td>61.2</td>
</tr>
<tr>
<td>1.0</td>
<td>158.0</td>
<td>68.0</td>
</tr>
</tbody>
</table>

It will be remembered that all our assumptions have been such as to favor large emission; we have assumed the maximum possible temperature gradient, the absence of all absorbers other than ammonia, a minimum value for the high-pressure absorption by ammonia, and complete lack of ionization at great depths. It seems very likely that one or more of these assumptions would in fact be violated, thereby making the agreement even worse. We are therefore compelled to the conclusion that a hot atmosphere cannot account for the bulk of the radio emission.

We find, however, that, when the disk temperatures of some 100$^\circ$K predicted by Table 2 for 3-cm wavelengths are subtracted from the observed values, only about a third to half the flux remains to be accounted for by some other mechanism. This fraction, amounting to some 5 to 8$^\circ$K cm$^{-1}$, is close to the amount expected on the basis of the longer-wavelength observations. We have evidence here, then, that the contribution to the flux by the atmosphere for 3-cm wavelength is probably substantial. Observations at shorter wavelengths will therefore yield information about the outer layers of the Jovian atmosphere in accordance with the theory here presented. The predicted spectrum for small $\lambda$ (but $\lambda > \lambda_0$, the ammonia resonance) is

$$T_D = (4/\gamma + 3)([\gamma - 1/2])! \cdot T_e (p_0/\Delta \nu)^{\gamma - 1}(\lambda/\lambda_0)^{\gamma - 1}$$

where $\lambda_0 = \lambda \tau_0$, with $\tau_0$ given by equation 8. Thus, for $\gamma = 1.56$, $T_D \sim \lambda^{-0.6}$, and the coefficient depends on ammonia abundance in the upper layers.

FREE-FREE EMISSION BY THE IONOSPHERE

Origin in Jupiter's ionosphere is an attractive hypothesis because, if saturation is neglected, the emission is independent of wavelength as required. Since $T_D \leq T$, we require a temperature of at least 70,000$^\circ$K. Such a temperature is an order of magnitude higher than that of the earth's ionosphere, but it cannot be ruled out since the chemical composition of the Jovian ionosphere is so different.

From the usual formulas for free-free emission by a medium of singly charged ions, of temperature $T$ and electron density $n_e$, we can show that the brightness temperature of a ray making angle $\cos^{-1} \mu$ with the vertical is

$$T_B = T \tau / \mu = 1.1 \times 10^{-22} T^{-1} \mu^{-1} \lambda^2 \int n_e^2 ds$$

(11)

so that the disk temperature (ignoring the small region near $\mu = 0$ which is saturated) is

$$T_D = 2.2 \times 10^{-22} T^{-1} \lambda^2 \int n_e^2 ds$$

(12)
It follows that to achieve a flux, $T_D/\lambda^2$, equal to about $10^9$ K cm$^{-2}$, we must have
\[
\int n_e^2 \, dz \sim 4.5 \times 10^{25} T^4 \text{ cm}^{-5}
\]
Since $T$ must be at least 70,000 K, this means an $\int n_e^2 \, dz$ of at least $1.2 \times 10^{25}$ cm$^{-1}$. In the first section we saw that, if $H < 6.4$ gauss, the critical-frequency argument implies that $n_e < 3.2 \times 10^{14}$ cm$^{-3}$, and if the thickness of the ionosphere is taken as less than 1000 km,
\[
\int n_e^2 \, dz < 10^{21} \text{ cm}^{-5}
\]
more than four orders of magnitude too small.

If $H > 6.4$ gauss, low frequencies may be transmitted through much higher electron densities—up to $5 \times 10^5 H$ cm$^{-3}$ according to the first section. We conclude that a 600-gauss field would allow the 18 Mc/s bursts to escape even if $n_e$ was as high as $3 \times 10^9$ cm$^{-3}$, and such a high density could account for the decimeter emission. Such a situation does not seem possible on other grounds, however. If we consider how the ionosphere is maintained against recombinations, we have that the number of ionizations per cm$^2$ per sec equals $\alpha \int n_e^2 \, dz$, where $\alpha$ is the recombination coefficient. Apparently we can get by with a small source of ionization if $\alpha$ is small. About the smallest $\alpha$ is that appropriate to atomic hydrogen at 70,000 K, about $10^{-3}$ cm$^{-5}$ sec$^{-1}$. Even then we need $1.2 \times 10^{14}$ ionizations cm$^{-3}$ sec$^{-1}$ to maintain the proposed ionosphere. The ionizing flux from the sun at Jupiter is about $4 \times 10^8$ cm$^{-3}$ sec$^{-1}$ [Allen, 1955], again short by a factor of 3000. The only way out of this dilemma would seem to be to invoke the particle flux from the sun, which at times could have an ionizing power approaching what we need, since there may be $4 \times 10^9$ protons cm$^{-2}$ sec$^{-1}$ having energies of several thousand volts. But surely a field of 600 gauss would shield the bulk of the ionosphere from such a particle flux, as a much smaller field does for the earth.

We conclude that the required ionosphere is rather dense, too dense to be consistent with the transmission of 18 Mc/s bursts if the magnetic field is less than 6.4 gauss. If, on the other hand, the field is 600 gauss or more, the 18 Mc/s bursts would escape in any event, but there seems to be no source of ionization sufficient to maintain the ionosphere. Hence the decimeter waves cannot originate in Jupiter's ionosphere.

**Cyclootron Radiation by Non-Relativistic Electrons**

As the cyclotron frequency is $2.8H$ Mc/s, non-relativistic electrons trapped in fields between 150 and 1000 gauss would radiate at wavelengths between 10 and 70 cm. One may imagine, therefore, that Jupiter has a magnetic field of some 1000 gauss at the poles, in which is trapped a belt of electrons somewhat resembling the Van Allen belt of the earth.

The radiation from such electrons at the cyclotron frequency will of course tend to be reabsorbed owing to the cyclotron resonance. But, because of the magnetic field strength gradients necessarily present, no region absorbs exactly at resonance the radiation emitted by neighboring regions. Under these conditions, it can be shown that the integrated optical depth to free space is less than $\langle \pi T^2/\gamma \rangle n_e \approx n_e/4$, where $l$ is the scale of the magnetic field (\(\sim R^2\)) and $n_e$ the electron density in the belt. It follows that re-absorption is not important if the electron density is less than $4$ cm$^{-3}$. As the electron density is in the range 1 to $10$ cm$^{-3}$ in the earth's outer belt [Van Allen, 1959], we are probably safe in assuming that re-absorption may be ignored. This argument finds some confirmation in the fact that the observed spectrum shows no tendency toward saturation, under which condition $T_D$ would remain constant at $2(E)/3k$ as $\lambda$ varied.

We must therefore imagine that the observed spectrum largely reflects the distribution of electrons and the radiative efficiency in magnetic fields of various strengths. We shall not discuss this problem further here, beyond saying that a polar field of 1000 gauss, decreasing to some 150 gauss far from the planet, would provide the basis for the observed spectrum if the electrons were found at these and all intermediate field strengths.

We may, however, examine the energy requirements for this mechanism. From the well-known law for radiation by an accelerated charged particle we may write the total radiated power (integrated over frequency) as
\[ P = \frac{32\pi^2 e^2 \nu_1^2}{9cE_0} \int_{\text{volume}} n_e H^2 E \, dV \]  \hspace{1cm} (13)

where \( \nu_1 \) is 2.8 Me/s, the cyclotron frequency for one gauss; \( E_0 \) is the rest energy of the electron; \( n_e \), the electron density; and \( E \), the electron energy. If we approximate the radiating region by a shell of radii \( R_1 \) and \( 2R_1 \), and take \( \langle H^2 \rangle = 10^5 \) gauss\(^2\) in accordance with the frequency requirements, this equation gives

\[ P = 10^{18} U \]  \hspace{1cm} (14)

where \( U \) is the electron energy density in electron volts cm\(^{-3}\). The total observed emission corresponds to \( 5 \times 10^6 \) ergs sec\(^{-1}\), so we require that \( U = 5\text{ev cm}^{-3} \). Such a value does not appear excessively high. The outer Van Allen belt contains some \( 10 \) to \( 100 \) electrons cm\(^{-3}\), with energies up to 60 kev [Van Allen, 1959]. It appears to be replenished by solar particles; if the same is to be true of Jupiter, we would require that the flux of particle energy from the sun exceed the flux of radio energy from Jupiter. Note that we may include the protons in the former since they will drag the electrons along with them.

A lower limit for the particle energy flux at the earth can be found from the intensity of the 'corpuscular E layer' in auroral zones; according to Kiepenheuer [1953] at least \( 0.1 \) erg cm\(^{-2}\) sec\(^{-1}\) strikes the earth in the form of particles in the auroral zones. If we allow for the greater distance from the sun and the fact that the above flux may represent a concentration by the earth's magnetic field over the average value, the particle energy flux at Jupiter still appears to be greater than the radio emission, which is about \( 10^{-4} \) erg cm\(^{-2}\) sec\(^{-1}\). It seems, therefore, that, on the basis of energy considerations, a belt of electrons trapped in a 1000-gauss field and replenished by the solar corpuscular emission could account for the decimeter radiation.

**Synchrotron Radiation by Relativistic Electrons**

By introducing relativistic electrons one may decrease the required field strength from the value of the previous section by a factor of \( \gamma^2 \), where \( \gamma \) is the energy in units of rest energy, since each electron radiates a spectrum of harmonics of \( \nu_1 \) the maximum of which is near \( \nu_1' \). At the same time, the energy requirements become more difficult to satisfy, since presumably far fewer relativistic than non-relativistic electrons will be available.

One source of fast electrons is, of course, cosmic rays. The fraction of cosmic-ray primaries which are electrons having 1 bev or more energy is known to be 0.6 per cent or less [Critchfield, Ney, and Oleksa, 1952]. This implies an upper limit of \( 4 \times 10^{-5} \) erg cm\(^{-3}\) sec\(^{-1}\) on their energy flux, only 5 per cent of the observed radio emission. Thus, even if the supposed primary electrons lost all their energy through radiation at decimeter wavelengths, they would not be numerous enough to explain the observations. In any event, the radiative efficiency must be much less than unity since they are near Jupiter for about 1 sec only.

Secondary electrons produced by collisions in the atmosphere of the earth feed the inner belt of trapped particles. However, the number again seems to be insufficient. Singer [1950] finds that secondary electrons have energies in the range from 10 to 30 Mev. Perlav, Davis, Kissinger, and Shipman [1952] find that the ratio of secondary electrons moving upward to primaries moving downward is 0.1 by number. Hence the energy flux in electrons leaving the top of the atmosphere is \( 3 \times 10^{-8} \) erg cm\(^{-2}\) sec\(^{-1}\); that is, only 4 per cent of the observed radio emission. Thus, secondaries appear too weak to account for the emission even if complete efficiency for radiation is assumed.

The corpuscular emission from the sun also contains fast electrons. Boischot [1959] discusses the so-called type IV solar radio emission, which is doubtless due to synchrotron radiation by fast electrons in the corona. These electrons are apparently accelerated in solar flares, and radiate for several hours a spectrum which places their energies in the range of several million electron volts. The number of fast electrons in a single event is of the order of \( 10^{24} \). Suppose for a moment that these electrons are radiated from the sun uniformly without energy loss in all directions. Then a fraction \( 10^{-4} \) or some \( 10^{27} \) electrons reach Jupiter, if we allow for an extended magnetic field. If each has an energy \( 10^{-4} \) erg and such events occur as frequently as all classes of flares at maximum ac-
tivity, some \(10^{-8} \text{ sec}^{-1}\), then the energy supplied to Jupiter is \(10^{6} \text{ erg sec}^{-1}\), only 1/50 of the observed emission. Since we have assumed a high frequency of such events and have ignored the tendency of the electrons to radiate most of their energy near the sun, it appears that the sun does not supply relativistic electrons directly in the necessary quantity.

On the other hand, we have already pointed out that the energy flux of non-relativistic particles from the sun is adequate to account for the emission. It is possible that a certain fraction of this flux is accelerated locally near Jupiter to relativistic energies. In fact, there is evidence that some acceleration does occur near the earth, since there is the well-known discrepancy between the energies (\(\sim 500 \text{ kev}\)) required to produce the observed ionization layer, and those inferred (\(\sim 20 \text{ kev}\)) from travel times. We cannot rule out the possibility that acceleration occurs near Jupiter, also. If so, \(\gamma\) could be considerably greater than 1, and the magnetic field strength requirement is reduced by a factor \(\gamma^2\). Since the particle energy flux does not greatly exceed the radio flux, however, rather high efficiency must be postulated for the acceleration process.

Observational Tests

Let us first summarize our previous conclusions. In the second section we concluded that it is highly unlikely that the atmosphere is responsible, and in the following section the ionosphere was ruled out. The next two sections indicated that radiation by electrons in a magnetic field is quite possible if the ultimate source of energy is the solar corpuscular radiation. It is not clear, however, whether a strong field and cyclotron radiation, or a weak field and synchrotron radiation, is expected. Let us consider various observations that could be made, and their interpretation.

Angular extent—The earth's outer Van Allen belt has some four times the diameter of the earth in the equatorial plane. If the same should be true of Jupiter, a diameter between 2'.1 and 3'.3 is expected for the radio source, in the Jovian equatorial plane. Unfortunately, this width is probably attained only for the low frequencies (because \(H\) is small at large distances from Jupiter) where resolution of radio telescopes is poor; perhaps the 21-cm interferometers having beamwidths of about 3' offer the best tool for this test. If, of course, there is broadening of the beam, we may definitely rule out origin in the atmosphere or ionosphere.

Spectrum at longer wavelengths—Evidently thermal emission contributes to the short-wavelength spectrum; we have already mentioned how further observations in this region can tell us about Jupiter's upper atmosphere. The long wavelengths are probably emitted by weaker magnetic fields, and so measures in this region will contribute to our understanding of the electron trapping at large distances. To interpret such data, a theory to connect spectrum with density-field relationships is needed. Presumably such a theory will be different for cyclotron and synchrotron radiation, and will help distinguish between them.

Polarization—One expects residual linear polarization with electric field parallel to Jupiter’s equator, if either type of electron-magnetic field interaction is responsible. Again a detailed theory is necessary to predict amounts; qualitatively, synchrotron radiation would seem to yield the larger effect because there is less dilution by elliptically polarized components from polar latitudes. Of course any polarization at all rules out atmospheric or ionospheric origin.

Variability—This should be a good test of our conclusion that the sun is the ultimate source of energy. Little variability is expected for a cosmic-ray source, whereas a solar source will be quite variable, by analogy with the outer Van Allen belt of the earth. Again, any variability rules out atmospheric origin. There is already some evidence for variability (McClain and Sloanaker, 1959; Drake, 1959), thus adding weight to our arguments that origin in electrons supplied by the sun is the most probable.

We conclude by emphasizing that distinguishing between cyclotron and synchrotron radiation is the most important step now. Is Jupiter's magnetic field 1000 gauss or more, or is it in fact much smaller? Further observations of the remarkable high-frequency Jupiter spectrum, coupled with a detailed theory, should give the answer.

It is a pleasure to acknowledge that Dr. F. D. Drake suggested this problem to me, and also
outlined most of the mechanisms here discussed. I am also grateful to Dr. L. Spitzer, Jr., for his encouragement and criticism.

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