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RADIO EMISSION FROM JUPITER AT A WAVELENGTH OF 31 CENTIMETERS

J. A. ROBERTS AND G. J. STANLEY
California Institute of Technology Radio Observatory
Owens Valley, California

INTRODUCTION

The first observations of the steady radio emission from Jupiter gave intensities consistent with radiation from a black body at a temperature close to the temperature of the Jovian clouds. Thus Mayer, McCullough, and Sloanaker,[1] at a wavelength of 3.15 cm, reported an equivalent disk temperature of 145° ± 18° K; Drake and Ewen,[2] at a wavelength of 3.75 cm, found a temperature slightly greater than 200° K, but estimated the error as perhaps as great as a factor of two; and Alsop, Giordmaine, Mayer, and Townes,[3] at 3.18 cm, found a temperature of 165° ± 17° K. These values are all close to the radiometric (infrared) temperature of 130° K reported by Menzel, Coblentz, and Lampland,[4] and since the optical measurements refer to the clouds in Jupiter's atmosphere, while the radio measurements could, for example, refer to the solid surface of the planet, the slight differences were not surprising.

However, measurements at a wavelength of 10.3 cm by Sloanaker indicated a considerably higher temperature.[5] Preliminary results gave a disk temperature of 580° K as the average of a number of observations varying individually from 400° to 900° K, and from recent measurements Sloanaker (private communication) suggests an average value of 700° K with variations of the order of 50%. In view of this great change in the radio emission between 3 and 10 cm, we have made a series of observations at a wavelength of 31 cm. These observations are reported here, together with a discussion of their implications. At this wavelength we find a mean disk temperature of 5500° K.

OBSERVATIONS

The observations were made with a 90-foot equatorially mounted radio telescope accepting two sidebands at wavelengths of approximately 30 and 32 cm. The beam width between half power points was 52′. The sensitivity of the receiver was such that Jupiter could be readily detected on a single drift curve (Fig. 1). Sixty records of reasonable quality were obtained on

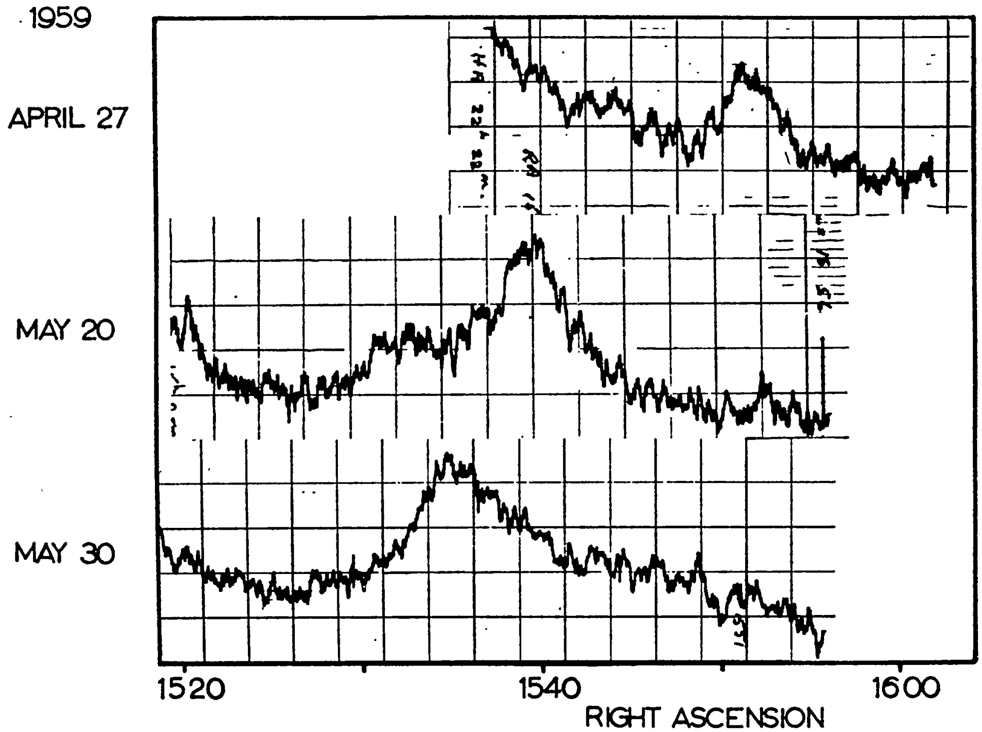

FIG. 1.—Three sample records showing the passage of Jupiter through the stationary antenna beam. Notice the changing background of cosmic noise particularly evident in the record of May 20.

28 nights between April 15 and June 17, 1959. Intensities were measured relative to the standard source, Virgo A, and in converting to absolute units of flux, or to disk temperature, a value of 3.0×10^{-24} watts m^{-2} $(c/s)^{-1}$ has been assumed for the flux from Virgo A (two planes of polarization). The intensities have been corrected for the varying distance of Jupiter and refer to a distance of 4.375 A.U., i.e., to a polar semidiameter of 21″.0.

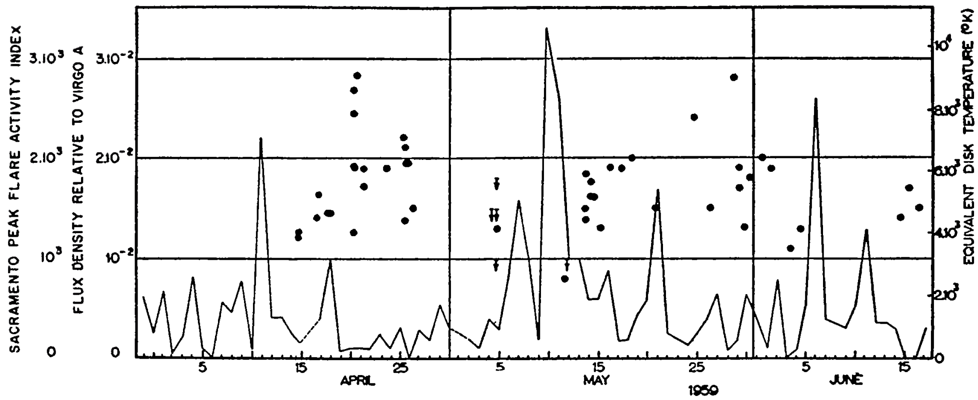

FIG. 2.—Observed intensities of Jupiter relative to Virgo A, corrected to a distance of 4.375 A.U. The scale of disk temperature at the right is based on a flux of 3.0×10^{-24} watts m^{-2} $(c/s)^{-1}$ for Virgo A (two planes of polarization). The curve shows the Sacramento Peak Flare Index.

The observed intensities are plotted against the date of observation in Figure 2, and a histogram of values is given in Figure 3. The mean flux density was found to be 1.7×10^{-2} times the flux from Virgo A, or 5.2×10^{-26} watts m^{-2} $(c/s)^{-1}$. This corresponds to a disk temperature of 5500° K. The individual

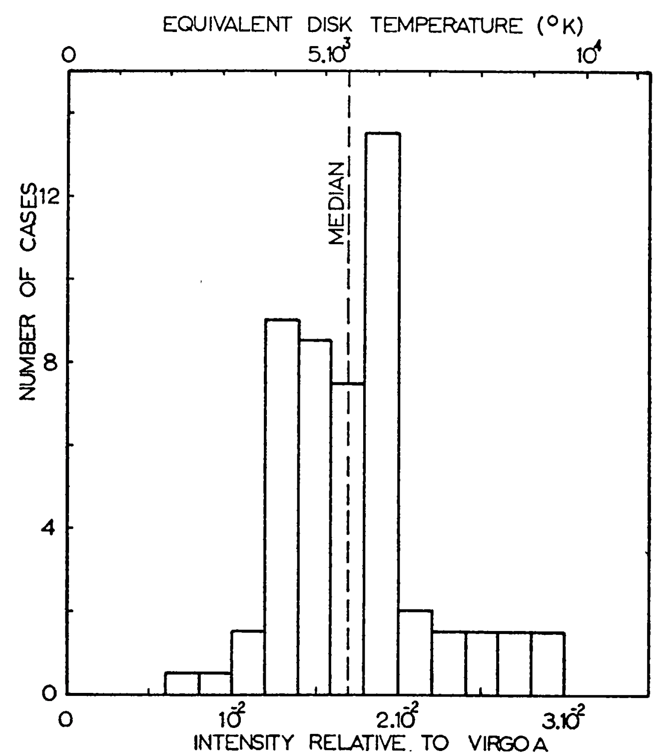

FIG. 3.—Histogram of the values given in Figure 2.

measurements show considerable scatter about this mean value, the extreme range being from 0.8 to 2.9×10^{-2} times the flux from Virgo A. Eighty per cent of the values lie between 1.2 and 2.0×10^{-2} times the Virgo A flux, or between 3800° and 6400° K.

We have tried to assess the reality of these variations by comparing the degree of variation with that in the measurements of other weak, but presumably constant, sources. For any one such source we do not have such an extensive set of observations as for Jupiter, but by combining the observations of a number of sources in a plausible fashion we have concluded that the variations found in the Jupiter values were not significantly greater than those for the other weak sources. In spite of this conclusion, we did check for a correlation with Jovian longitude, both system I and system II, and also for a correlation, either direct or delayed, with the Sacramento Peak Flare Index. In no case was there any significant correlation.

DISCUSSION

Concurrently with the present observations, measurements were made by Drake at a wavelength of 22 cm[6] and at a wavelength of 68 cm.[7] These values, together with an upper limit to the emission at 3.5 m given by Mills *et al.*[8] and the values already mentioned, have been used to derive the spectrum shown in Figure 4. The equivalent disk temperature rises sharply with increasing wavelength, while the flux density remains sensibly constant, at least for wavelengths from 10 cm upwards. At 3 cm the flux is greater by a factor of 2 to 3, presumably due to the λ^{-2} black body flux from the Jovian clouds becoming appreciable.

The immediate inference from these high disk temperatures is the existence, presumably in the atmosphere of Jupiter, of material that is in a very different state from the material observed optically. Unless the diameter of the radio source is very much greater than that of the planet, the radio source must contain particles with energies corresponding to temperatures of at least 10^5 degrees and probably greater.*

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* We neglect here the possibility of reduced, or even negative, absorption in randomly emitting processes, as discussed by Twiss.[9]

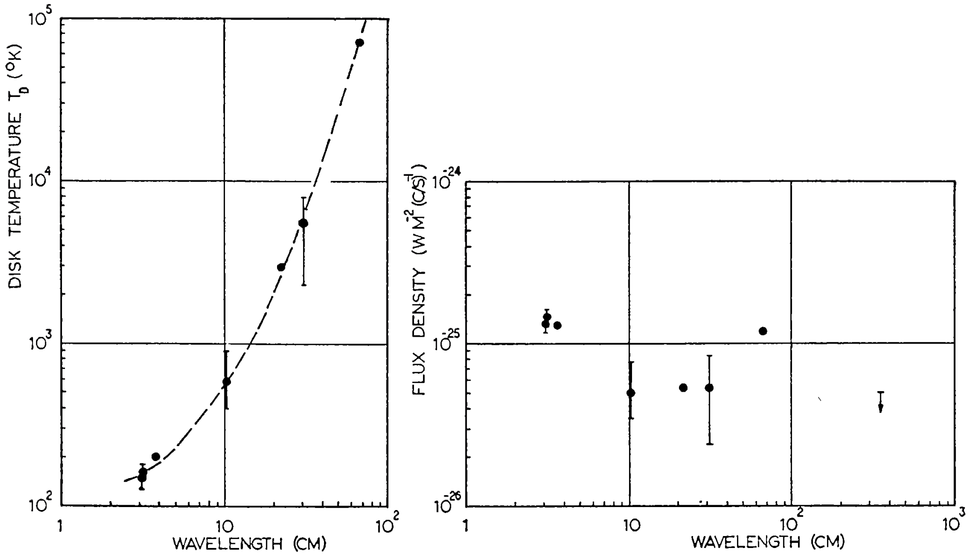

FIG. 4.—The spectrum of the steady emission from Jupiter.

Two radiation processes are believed to be operative in cosmic sources of *continuum* radio emission, namely free-free transitions and synchrotron radiation. We shall discuss each of these briefly as the possible mechanism of generation of the high-frequency radio emission from Jupiter.*

A JOVIAN CORONA?

We consider first the free-free emission hypothesis, and for simplicity discuss emission from an isothermal region. The observed flat spectrum then implies that the region is optically thin, with the kinetic electron temperature, T_ϵ, greater than the highest brightness temperature observed. In the absence of knowledge of the extent of the radio source we use the observed disk temperature T_D as an estimate of the brightness temperature T_B. If the radio emission comes from an area larger than the optical disk, this will overestimate T_B, but it should be sufficiently accurate for order-of-magnitude calculations.

In terms of the wavelength, electron density, and electron temperature, the brightness temperature due to free-free transitions is, for an optically thin region, approximately[10]

$$T_B = 1.6 \times 10^{-22} \lambda^2 T_\epsilon^{-1/2} \int n_\epsilon^2 \, ds \quad \text{(cgs units)}.$$

* Note added in proof: The recent discussion by Field[21] of radiation from Jupiter in some ways complements the discussion given here.

To obtain a *minimum* estimate for $\int n_\epsilon^2\, ds$ that will yield the observed brightness temperature, we use the minimum allowable value for T_ϵ, or, from Figure 4, say 10^5 °K. Then, by setting T_B equal to the observed disk temperature, we have, for wavelengths from 10 to 70 cm,

$$\int n_\epsilon^2\, ds \geqq 10^{25}\ \text{cm}^{-5}. \qquad (1)$$

It is convenient to write

$$\int n_\epsilon^2\, ds = \overline{n_\epsilon^2}\, R_J,$$

where $\overline{n_\epsilon^2}$ is the mean square electron density over a distance equal to the radius of Jupiter, $R_J = 7.1 \times 10^9$ cm. Then, to meet the inequality (1) we require that

$$(\overline{n_\epsilon^2})^{1/2} \geqq 4 \times 10^7\ \text{cm}^{-3}. \qquad (2)$$

Thus the hypothesis that the continuum radio emission from Jupiter arises from free-free transitions in a high-temperature atmosphere requires that the kinetic temperature, T_ϵ, of the atmosphere be $\geqq 10^5$ °K and that the root mean square electron density over a distance R_J be $\geqq 4 \cdot 10^7$ cm^{-3} (or correspondingly greater if T_ϵ is greater). These densities are similar to those in the solar corona, while the temperatures are lower by a factor of the order of 10. It would seem, therefore, that if such an atmosphere exists it might be possible to detect it by the optical techniques used for observing the solar corona outside eclipse, namely by using a coronagraph to record the spectral-line emission.

In the absence of such optical tests we may also speculate on the theoretical possibility that such an atmosphere exists on Jupiter. A cold, and presumably solid, planet hardly seems a likely source of such an atmosphere, but Chapman[11] has recently suggested that the corona of the sun extends throughout the planetary system, and in the vicinity of Jupiter he predicts a temperature $\sim 10^5$ °K. However, the density of this coronal extension is only about 10^3 cm^{-3} or less than 10^{-4} of the density needed to account for the radio emission. Hence, if this solar material is the source of the radio emission, there must be some process by which Jupiter captures and compresses a large quantity of it.

The density of the atmosphere which Jupiter would collect from this material by gravitational attraction may be estimated readily by a modification of the analysis of Chapman.[11] We assume that the medium is fully ionized hydrogen of uniform temperature, T, and in the absence of the planet, of uniform density, n_0. The pressure p, density ρ, number density of particles n, and the gravitational acceleration g, are all functions of the distance R from the center of the planet. Values of these quantities at the surface of the planet are indicated by the subscript J.

For statical equilibrium

$$dp = -\rho g \, dR.$$

Using the relations

$$p = nkT \quad \text{and} \quad \rho = nM,$$

where M is the mean molecular mass of the gas, this equation becomes

$$d(\ln n) = -dR/H, \tag{3}$$

where the scale height

$$H = kT/Mg.$$

Since

$$g = g_J \, (R_J/R)^2,$$

we must have

$$H = H_J \, (R/R_J)^2,$$

and the integral of equation (3) is then

$$n = n_0 \exp{(R_J{}^2/H_J R)}.$$

The constant of integration has been chosen so that at great distances the density tends to the value in the absence of the planet.

If we now insert the numerical values[10] and take $T = 10^5$ °K, we find $H_J = 6.4 \times 10^9$ cm. Hence, even at the surface of the planet ($R = R_J = 7.1 \times 10^9$ cm) the increase in density, n/n_0, is only ~ 3. Clearly then, gravitational attraction alone is not able to provide the required compression.

Whether a magnetic field on the planet could trap sufficient material is a much more difficult question to answer. For protons at a temperature of 10^5 degrees the magnetic force evH in a field of 1 gauss is some 10^7 times as great as the gravitational force mg. It therefore seems plausible that magnetic forces could retain a sufficiently dense corona on Jupiter. However we have not been able to make a quantitative evaluation of this possibility, which evidently requires the development of a theory of magnetic trapping.

A JOVIAN VAN ALLEN BELT?

For the alternative theory that the emission is synchrotron radiation, the requirement is for relativistic particles and a magnetic field. This type of theory was proposed by Drake,[6] who suggested that Jupiter is surrounded by a belt of relativistic particles trapped by a magnetic field—a belt comparable to the Van Allen belt on the earth.

The only evidence for a magnetic field on Jupiter appears to be the polarization of the low-frequency radio bursts, which, according to Carr,[12] implies a field of about 7 gauss. With a field of this order, electrons emitting synchrotron radiation in the 10- to 100-cm wavelength range would need to have energies of 1 to 30 Mev, while protons would require energies of 10^5 to 10^6 Mev. In the case of the earth, the particles in the lower Van Allen belt are protons, mostly with energies below 10^3 Mev.[13] The particles in the upper belt are believed to be electrons (Snyder[14]), which are detected by the bremsstrahlung γ rays that they produce in the rocket casing. The electrons are also predominantly nonrelativistic ($\sim$25 kev), but occur in such numbers that an appreciable number have energies above 1 Mev. Vernov *et al.*[15] estimate that the number of electrons in the energy range dE at E falls off as E^{-6}, and from their data we show in the Appendix that the density of electrons with $E > 1$ Mev is about 3×10^{-7} electrons cm^{-3}.

The spectrum of synchrotron radiation depends on the energy distribution of the particles in association with the magnetic field intensity. When the energy distribution is the same at all points of the field, a distribution of the form $E^{-(1+\gamma)}$ leads to a radio spectrum of the form $f^{-\frac{1}{2}\gamma}$ (see, e.g., Hoyle[16]). Thus, the Van Allen distribution with $\gamma \sim 5$ would lead to a much steeper radio spectrum than that observed from Jupiter (approximately f^0 or $f^{-\frac{1}{2}}$—Fig. 4*b*). If the Jupiter radiation is synchrotron emission, either the energy distribution of the relativistic electrons is quite different from that in the earth's Van Allen belt, or the more energetic electrons are trapped in the stronger parts of the field. Since there seems to be no evidence for such a separation in the earth's belt, this may be taken as an argument against the synchrotron theory.

To estimate the density of relativistic electrons needed to account for the Jupiter radiation, we make the common approximation[17,18] that the emission spectrum of a single electron is

$$P(f) = 3.77 \times 10^{-27} E^{-2/3} H^{2/3} f^{1/3} \text{ erg sec}^{-1} (\text{c/s})^{-1},$$

for frequencies $f \leqq f_c$, and zero for $f > f_c$, where the critical frequency

$$f_c = 5.27 \times 10^{17} E^2 H \quad \text{c/s}.$$

In these equations E is the electron energy, H the magnetic field intensity, and all units are cgs. For an assembly of electrons uniform over depth D the brightness temperature will be

$$T_B(f) = (c^2/2kf^2)\, D \int_{E_c}^{\infty} n(E) \left\{P(f)/4\pi\right\} dE.$$

Here $n(E)$ is the energy distribution of the electrons, which according to Vernov *et al.* is of the form

$$n(E) = AE^{-6}.$$

The lower limit of integration

$$E_c = 4.03 \times 10^{-10} H^{-\frac{1}{2}} f^{\frac{1}{2}},$$

is the lowest energy that contributes to emission at frequency f. Performing the integration, we find

$$T_B = 2.98 \times 10^6 ADH^{7/2} f^{-9/2}.$$

If $H = 7$ gauss and $D = 10^{10}$ cm ($= 1.4\ R_J$), then for T_B to equal the observed disk temperature at 31 cm requires that the number of electrons with energies greater than 1 Mev be approximately 10^{-2} per cubic centimeter.

This exceeds the estimated density in the earth's Van Allen belt by a factor of the order of 3×10^4. However, the disparity may not be as great as appears at first sight. The density in the terrestrial belt apparently varies with time, and Vernov *et al.* quote Van Allen as measuring a flux 100 times as great as the flux that we have assumed.* It seems that we will have to await further observations of the terrestrial belt and a further understanding of its origin to assess the likelihood of electron densities of this order occurring on Jupiter.

CONCLUSION

Our discussion of the origin of the high-intensity decimeter radiation from Jupiter has not led to any definite conclusion. If the emission arises from free-free transitions, the r.m.s. electron density over a distance equal to the radius of Jupiter must be $\geqq 4 \times 10^7$ cm^{-3} and the temperature must be $\geqq 10^5$ degrees. We explored the possibility that Jupiter could collect such an atmosphere from hot interplanetary material. Gravitational forces alone are insufficient, but a magnetic field might prove adequate. Other sources of such an atmosphere, e.g., a conventional ionosphere, were not discussed, but ionospheric parameters have been estimated by others.[19]

If, on the other hand, the emission is synchrotron radiation from relativistic electrons spiralling in a field of a few gauss, there must be the equivalent of $\sim 10^{-2}$ electrons cm^{-3} with energies between about 1 and 100 Mev over a depth of 10^{10} cm. In the Van Allen belt of the earth, the density of such electrons is less by a factor of about 10^4. However, it seems that a more detailed knowledge of the belts, and particularly of their origin, is needed to assess the likelihood of these higher densities occurring on Jupiter.

Important radio observations that should be made in the future are the angular size of the source, the polarization of the radiation, and more accurate intensity measurements to ascertain whether there are any true variations of the source intensity. On

* Note added in proof: Van Allen and Frank give the density of electrons with $E > 2.5$ Mev as $\leqq 3 \times 10^{-5}$ cm^{-3} at 30,000 km on March 3, 1959.[22]

the optical side any possible means of measuring the magnetic field should be exploited, and it would also seem to be desirable to use a coronagraph to search for emission lines from a possible corona.

APPENDIX

As we need only an order-of-magnitude estimate of the density of electrons with energies greater than 1 Mev, we proceed in the following approximate fashion:

At the maximum of the outer belt Vernov *et al.*[15] found the x-ray flux under 1.9 mg cm^{-2} Al to be 2×10^{11} ev cm^{-2} sec^{-1} $sterad^{-1}$. They concluded that this flux was produced by electrons with an energy spectrum approximating

$$n(E) = AE^{-6},$$

the basic part of the energy detected coming from electrons with energies of the order of 25 kev. Such electrons would be stopped in the aluminum foil, and on the average a fraction $\sim 2.5 \times 10^{-4}$ of their energy would appear as x-rays (see, e.g., Evans[20]). Hence, the energy flux of the incident electrons is $\sim 8 \times 10^{14}$ ev cm^{-2} sec^{-1} $sterad^{-1}$.

This must be equal to

$$\int n(E)\, E\, (v/4\pi)\, dE,$$

where v is the speed of an electron of energy E. For the dominating nonrelativistic energies $v = (2\,E/m)^{\frac{1}{2}}$. Taking the lower limit of integration as 25 kev, we evaluate A and hence determine the number of electrons having an energy greater than 1 Mev as approximately 3×10^{-7} electrons per cubic centimeter.

ACKNOWLEDGMENTS

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