BELL TELEPHONE LABORATORIES
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MURRAY HILL, NEW JERSEY
SUMMIT 6-6000

August 16, 1946

IN REPLY REFER TO

1170-CHT-CMH

REPLYING TO

MR. GROTE REBER

212 W. Seminary Avenue

Wheaton, Illinois

Dear Mr. Reber:

Your letter of July 18th is much appreciated. I had overlooked the data of Friis and Feldman. This data is very interesting, although sketchy. Unfortunately Feldman tells me there is little hope of obtaining more data soon with the array of antennae.

I have finally finished writing up the bulk of the theoretical work I've been carrying on in my spare time concerning cosmic noise. It must be processed by our publication department, however, before release. I would like very much to have your comment on the couple of paragraphs concerning your measurements which I have enclosed. My understanding of your antenna system is not good; but as you will see fundamental considerations lead me to somewhat lower temperatures or average radiation densities than given in your paper. I also don't understand how you obtain a beam width 6 to 8 degrees wide with a ratio of mirror diameter to wavelength of 5.1. Standard formulae assuming uniform mirror illumination give a total beam width between half-power points of about 12 degrees. Perhaps there is some simple point which I am overlooking. I hope you can clear this up for me.

Am very glad to hear that you and Dr. Greenstein are engaged in reviewing the cosmic and sun noise work, and hope you will send me a copy of your work when it is complete.

Sincerely yours,

Chas. H. Townes

CHAS. H. TOWNES

Attached.

In discussing some of the other radio results, a fundamental thermodynamic relationship will be used. An amplifier receives from a perfectly matched, lossless antenna power $kT\Delta\nu$ if T is the temperature of space surrounding the antenna. This can be shown by examining the noise power transmitted between two equal parallel-connected resistors r_1 and r_2 at temperature T. r_1 delivers Johnson noise of power $kT\Delta\nu$ to r_2 and r_2 delivers an equal amount back to r_1. If r_2 is replaced by a matched, lossle$$ antenna, r_1 must radiate into space power equal $kT\Delta\nu$ and if the surrounding space is at the same temperature it receives $kT\Delta\nu$ to maintain thermal equilibrium. If reflections or losses are present in the antenna, the transmitted or received power is decreased accordingly.

Reber's results at 160 megacycles are given both in terms of total power received and radiation power per square centimeter per circular degree per frequency interval. To obtain the latter, he assumes that radiation of only one plane of polarization is received by the antenna, and uses a beam width 6° by 8°. If we compute the temperature from $kT\Delta\nu$ we obtain 1370°K. If we use his figures for power per square centimeter per circular degree per frequency interval and apply formula (12), the temperature is 5100°K. This latter figure was apparently used by Henyey and Keenan, and later by Greenstein, Henyey and Keenan[17]. However, the inconsistency between 1370° abd 5100° must be explained either by an underestimation of the width of the main

formula is Power per freq. interval per cm² per steradian $= \frac{2k\nu^2 T}{c^2}$

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17. Greenstein, Henyey, and Keenan, Nature 157, 805 (1946).

antenna lobe, or by the presence of important minor lobes. It appears more correct to the author to make no assumptions about the antenna pattern and to take 1370°K as the average temperature seen by the antenna. This value should be good if transmission from the receiver through the antenna to space is perfect except for the 15% loss in the mirror pointed out by Reber.

INTERPRETATION OF RADIO RADIATION FROM EXTRATERRESTRIAL SOURCES

by Charles Hard Townes
Bell Telephone Laboratories,
Murray Hill, N. J.

Radio frequency radiation originating outside the earth's atmosphere was first discovered by Jansky[1] at a frequency of ~~15~~ 20.6 megacycles per second. Since then Reber[2] and others[3,4] have measured the intensity of this radiation or "noise" at other frequencies and fixed its direction more exactly. Jansky[5] suggested that the radiation he detected may have come from ionized gas in the Milky Way. Reber[6] made a rough calculation for such a mechanism and Henyey and Keenan[7] first applied a more quantitative theory and showed that the magnitude of radio radiation from the Milky Way agrees approximately with the radiation one might expect from free electron collisions with protons in interstellar space. They assumed the accepted values of electron density approximately one per c.c. and temperature equal to 10,000°K.

This paper purposes to examine briefly the theory of production of long-wave radiation by collisions between electrons and ions, to compare the radio data available with this theory, and to discuss two conclusions noted earlier.[8]

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1. Jansky, I.R.E. 20, 1920 (1932)
2. Reber, Astrophys J. 100, 297 (1944)
3. Friis and Feldman, I.R.E. 25, 841 (1937)
4. Hey, Phillips and Parsons, Nature 157, 297 (1946)
5. Jansky, I.R.E. 23, 1158 (1935)
6. Reber, I.R.E. 28, 68 (1940)
7. Henyey and Keenan, Astrophys J. 91, 625 (1940)
8. Townes, Phys. Rev. 69, 695 (1946)

1. Radio data calls for a temperature for inter-stellar electrons nearer 100,000° than the usually assumed 10,000°.

2. The sun's corona may radiate enough radio-frequency energy to increase appreciably the sun's total radiation and apparent diameter as measured in this frequency range.

Theory

Kramers[9] gave a classical derivation for continuous X-ray emission produced by bombarding nuclei with electrons. In doing so he obtained an expression which is also applicable to the radio frequency radiation produced by collisions between electrons and hydrogen ions in interstellar space. His expression for the amount of radiation per cubic centimeter per frequency interval per second is

$$\frac{dE}{dt} = \frac{32\pi}{3} \frac{e^6 n^2}{c^3 m^2 v} \log \left(\frac{mv^3}{1.78\,\pi\,\nu\,e^2}\right) \qquad (1)$$

where n = density of ions and hence of electrons.

e, m, v = electronic charge, mass, and velocity respectively.

c = velocity of light.

ν = the frequency considered.

To obtain the absorption coefficient of the ionized gas, $\frac{dE}{dt}$ must be multiplied by $\frac{c^2}{8\pi kT\nu^2}$, so that

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9. Kramers, Phil, Mag. 46, 836 (1923).

$$\gamma = \frac{4e^6}{3kTm^2cv} \frac{n^2}{v^2} \log \left(\frac{mv^3}{1.78\pi ve^2}\right) \tag{2}$$

Averaging over a Maxwellian velocity distribution as an approximation to the actual unknown electron velocity distribution, the absorption coefficient becomes

$$\gamma = \frac{8e^6}{3\sqrt{2\pi}\,(kTm)^{3/2}c} \frac{n^2}{v^2} \log \left[\frac{(2kT)^{3/2}}{4.23\pi ve^2 m^{1/2}}\right] \tag{3}$$

Gaunt,[10] Maue,[11] and Menzel and Pekeris[12] have given a quantum-mechanical treatment. Adapting equation (2.28) of Menzel and Pekeris to the long wavelength limit

$$\gamma = \frac{8\pi e^6}{3\sqrt{6\pi}\,(kTm)^{3/2}c} n^2/v^2\, \bar{g}_{III}$$

where $\bar{g}_{III} = \int_0^\infty \frac{\sqrt{3}}{\pi} \log \left(\frac{4v'}{v}\right) e^{-hv'/kT}\, d\left(\frac{hv'}{kT}\right)$

or $$\gamma = \frac{8e^6}{3\sqrt{2\pi}\,(kTm)^{3/2}c} \frac{n^2}{v^2} \log \frac{4\,kT}{1.78\,hv} \tag{4}$$

This equation again assumed a Maxwellian velocity distribution.

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10. Gaunt, Phil. Trans. A, 229, 163 (1930)
11. Maue, Ann. der Phys. 13, 161 (1932)
12. Menzel and Pekeris, Monthly Notices of R.A.S. 96, 77 (1935)

Equations (3) and (4) agree very well numerically as one might expect because the electron behavior is essentially classical under the conditions of interest. There are two somewhat disturbing features of these formulae, however. One is that logarithms in the two expressions show different functional dependence on the constants of the problem. Thus the quantum-mechanical expression (4) depends on h and would be divergent rather than approach the classical expression if h were allowed to approach zero. In addition, both formulae (3) and (4) require a divergent expression for the energy emitted per c.c. per second per frequency interval as v approaches zero. This is shown by (1).

To resolve these difficulties, an attempt was made to obtain a classical approximation somewhat more suited to the problem at hand than that given by Kramers. We first calculate the amount of radiation produced by collisions with impact parameters (distance between positive ion and asymptote of electron path) less than r_o. r_o is taken so small that the phase of the radiation does not change appreciably during collision and the electron trajectory is assumed to be unaffected by radiation. The contribution to the average energy emitted per collision per frequency interval by collisions within this radius is

$$\Delta E = \frac{32x\ e^6\ n^{2/3}}{3\ m^2\ c^3\ v^2} \log \left(1 + \frac{m^2\ v^4\ r_o^{\ 2}}{e^4}\right)^{1/2} \qquad (5)$$

And the energy emitted per c.c. per frequency interval per second due to these collisions

$$\frac{dE_1}{dt} = \frac{32\pi e^6 n^2}{3 m^2 c^3 v} \log \left(1 + \frac{m^2 v^4 r_o^2}{e^4}\right)^{1/2} \tag{6}$$

From radius r_o to radius $\frac{1}{2n^{1/3}}$ the approximation is made that the electron path is a straight line and the radiation phase allowed to change during the duration of the collision. $\frac{1}{2n^{1/3}}$ is one-half the distance between ions, hence only the field of the closest ion is considered. The resulting contribution due to these collisions is

$$\frac{dE_2}{dt} = \frac{32\pi e^6 n^2}{3 m^2 c^3 v} \left\{ \frac{\pi\nu}{vn^{1/3}} K_o\left(\frac{\pi\nu}{vn^{1/3}}\right) K_1\left(\frac{\pi\nu}{vn^{1/3}}\right) - \frac{2\pi\nu r_o}{v} K_o\left(\frac{2\pi\nu r_o}{v}\right) K_1\left(\frac{2\pi\nu r_o}{v}\right) \right\} \tag{7}$$

Here K_1 and K_o are Bessel functions.[13]

An approximation appropriate to the radiation observed from intersteller gas ($\nu \approx 10^8$ sec^{-1}, $v \approx 10^8$ cm/sec, $n \approx 1$ cm^{-3}) gives

$$\frac{dE_2}{dt} = \frac{32\pi e^6 n^2}{3 m^2 c^3 v} \log \frac{v}{2\pi\nu r_o}$$

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13. Whittaker and Watson, Modern Analysis p. 373 (Cambridge Press 1935).

so that

$$\frac{dE}{dt} = \frac{dE_1}{dt} + \frac{dE_2}{dt} = \frac{32\pi\ e^6\ n^2}{3\ m^2\ v\ c^3} \log \frac{mv^3}{2\pi\nu e^2} \qquad (8)$$

since

$$\frac{m^2\ v^4\ r_o^2}{e^4} \gg 1$$

This is essentially the same as Kramers' expression (1). For very small v or large n, however, such that $\frac{\pi\nu}{vn^{1/3}} \ll 1$

$$\frac{dE_2}{dt} = \frac{32\pi\ e^6\ n^2}{3\ m^2\ c^3\ v} \log \frac{1}{2n^{1/3} r_o}$$

and

$$\frac{dE}{dt} = \frac{32\pi\ e^6\ n^2}{3\ m^2\ c^3\ v} \log \frac{mv^2}{2\ e^2\ n^{1/3}} \qquad (9)$$

Thus the apparent divergence of $\frac{dE}{dt}$ for small v in Kramers' expression is due to considering collisions with only one ion at a time and allowing an infinite radius of interaction between each electron and each ion. Expression (9) removes this difficulty. The approximation given by Kramers does not, however, introduce appreciable error for cases of interest to this paper.

Although the work of Menzel and Pekeris is more recent and comprehensive than that of Gaunt, the latter's paper was examined in an attempt to explain the apparent discrepancy between the quantum-mechanical and classical expressions because his exposition is more detailed. Gaunt gives an expression (5.38) for the absorption coefficient involving a summation

$$\sum_{k=1}^{\infty} \frac{k\lambda^{-k}}{k^2+n^2}$$

where

$$n = \frac{2\pi e^2}{hv}$$

$$k = \frac{2\pi m p v}{h}$$

p = impact parameter or the distance between positive ion and asymptote of the electron path.

$\lambda = \frac{v}{v'}$, or the ratio of the initial electron velocity to the final velocity after emission of quantum $h\nu$.

This series Gaunt approximates by $\sum_{k=1}^{\frac{1}{\lambda-1}} \frac{k}{k^2+n^2}$ which he evaluates as $\log \frac{1}{\lambda-1} = \log \frac{mv^2}{2h\nu}$. This is the term responsible for the logarithmic part of (4). In evaluating the sum, Gaunt has evidently assumed that $n \sim o$. A more accurate value for $\sum_{k=1}^{\frac{1}{\lambda-1}} \frac{k}{k^2+n^2}$ is $\log \frac{1}{(\lambda-1)(1+n^2)^{1/2}} \approx \log \frac{mv^3}{4\pi e^2\nu}$. This expression now has the form of the classical result, and is not divergent as $h \to o$. Actually Gaunt's approximation $n \approx o$ is not a very bad one for the conditions of present interest. If ν is very small, or n large so that $\frac{\pi\nu}{vn^{1/3}} \ll 1$, the sum should not be from $k = 1$ to $k = \frac{1}{\lambda - 1}$, but its upper limit should be determined by the distance between ions, or $k = \frac{\pi m v}{h n^{1/3}}$. The sum then becomes $\log \frac{m v^2}{2 n^{1/3} e^2}$ which agrees with the logarithm of the classical expression (9) for small v and does not diverge as $v \to o$. It would appear that Maue, and Menzel and Pekeris may have made similar approximations ($n = \frac{2\pi e^2}{hv} < 1$ and $\frac{\pi v}{v n^{1/3}} \gg 1$) which give their expressions for the long wavelength limit the form (4).

Having satisfied ourselves concerning the apparent inconsistencies of (3) and (4), we may use either formula for cases of interest to this paper. Actually (3) will be used below as it appears to be more accurate, though differences between the two are less than 10% and quite insignificant. From (3) the apparent temperature of the Milky Way judged by the intensity of radiation of frequency v is

$$T_a = T\left\{1 - e^{-\gamma s}\right\} = T\left\{1 - e^{-10^{-2} \frac{n^2}{v^2 T^{3/2}} \left(19.7 - \log \frac{v}{(T)^{3/2}}\right) S}\right\} \quad (10)$$

where S is the extent of ionized gas in the direction of observation,

n is the density of positive ions, assumed uniform and composed largely of hydrogen,

T is the "temperature" of free electrons or $T = \frac{m\overline{v^2}}{3k}$.

For reasonable values $n = 1$ and $T = 10{,}000°$, and $S = 60{,}000$ L.Y.

in the long direction of the Milky Way, $\gamma S = 1$ for $\nu = 10^8$ cycles/sec. The Milky Way should then give maximum temperatures approximately 10,000° for $\nu \ll 10^8$. For frequencies so great that the $\gamma S \ll 1$, we have

$$T_a \approx \frac{10^{-2}\, n^2}{\nu^2\, T^{1/2}} \left(19.7 - \log \frac{\nu}{T^{3/2}}\right) S \tag{11}$$

so that the apparent temperature is approximately inversely proportional to ν^2. Thus for high frequencies the radiation per unit area per unit solid angle per unit time per frequency interval is approximately independent of frequency since the radiation power is

$$P = \frac{2\, k\, \nu^2\, T_a}{c^2}\, \Delta\nu \text{ per cm}^2 \text{ per steradian} \tag{12}$$

Radio Data and Its Analysis

Actual radio measurements agree with the expectation that the radiation power is independent of frequency at high frequencies. They also agree with the expected variation with S, or the path length through the Milky Way as shown well by the intensity contours of Reber and of Hey, Phillips, and Parsons. Maximum temperatures at low frequencies are, however, considerably higher than expectations.

Table 1 gives radio measurements from a number of sources expressed in terms of apparent temperature. These values have been reduced from the reported results which are usually expressed in other terms. A discussion of their reduction is given below.

Table 1 also compares the measurements with two attempts to fit the results by formula (4). In each case a temperature T is assumed and n is determined to fit Reber's measurement at 160 megacycles. The value of n so determined is consistent with other estimates[14] and probably more accurate than they if the radio radiation is produced by the mechanism discussed here.

Dicke measured the temperature of interstellar space at microwave frequencies with a microwave radiometer described recently.[15] He has informed the writer that since no detectable radiation was found, he concludes the temperature must be less than 30°K. Southworth[16] also looked for radiation from the Milky Way at microwave frequencies and found none. His sensitivity was somewhat less than that of Dicke.

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14. Dunham, Proc. Am. Phil. Soc. 81,277 (1939), also see ref. 7.
15. Dicke, Rev. Sc. Instr. 17,268 (1946)
16. Southworth, Jl. Franklin Inst. 239,285 (1945)

TABLE 1

Observer	Frequency Cycles/Sec.	Max. Apparent Temperature Degrees K	Max. Theoretical Apparent Temp. Assuming n = 0.63/c.c. T = 10,000°K	Max. Theoretical Apparent Temp. Assuming n = 1.1/c.c. T = 150,000°K
Dicke	3×10^{10}	<30	<5	<5
Reber	480×10^{6}	100-200	140	140
	160×10^{6}	1370	1370	1370
Hey, Phillips & Parsons	64×10^{6}	10,600	6000	9000
Jansky	18×10^{6}	100,000	10,000	84,000
Friis and Feldman	9.5×10^{6}	120,000	10,000	140,000

In discussing some of the other radio results, a fundamental thermodynamic relationship will be used. An amplifier receives from a perfectly matched, lossless antenna power $kT\Delta v$ if T is the temperature of space surrounding the antenna. This can be shown by examining the noise power transmitted between two equal parallel-connected resistors r_1 and r_2 at temperature T. r_1 delivers Johnson noise of power $kT\Delta v$ to r_2 and r_2 delivers an equal amount back to r_1. If r_2 is replaced by a matched, lossless antenna, r_1 must radiate into space power equal $kT\Delta v$ and if the surrounding space is at the same temperature it receives $kT\Delta v$ to maintain thermal equilibrium. If reflections or losses are present in the antenna, the transmitted or received power is decreased accordingly.

Reber's results at 160 megacycles are given both in terms of total power received and radiation power per square centimeter per circular degree per frequency interval. To obtain the latter, he assumes that radiation of only one plane of polarization is received by the antenna, and uses a beam width 6° by 8°. If we compute the temperature from $kT\Delta v$, we obtain 1370°K. If we use his figures for power per square centimeter per circular degree per frequency interval and apply formula (12), the temperature is 5100°K. This latter figure was apparently used by Greenstein, Henyey and Keenan[17] in their comparison of recent radio data with the theoretical curve given by Henyey and Keenan. The inconsistency between 1370°

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17. Greenstein, Henyey and Keenan, Nature 157, 805 (1946).

and 3100° must be explained either by an underestimation of the width of the main antenna lobe, or by the presence of important minor lobes. Reber informs the writer that the beam width 6° by 8° he assumed is indeed in some doubt. If one uses the diffraction pattern of a uniformly illuminated parabola of the size used by Reber, the expected beam is a cone of diameter approximately 12°. Use of this beam width and formula (12) gives a temperature of approximately 2000°. It appears more correct to the author to make no assumptions about the antenna pattern and to take 1570°K as the average temperature seen by the antenna. This value should be good if transmission from the receiver through the antenna to space is perfect except for the 15% loss in the mirror pointed out by Reber.

Reber's measurements at 480 megacycles have not yet been published, but he informs the writer that radiation energy is very nearly the same at this frequency as at 160 megacycles. On this basis, the apparent temperature is one-ninth that at 160 megacycles.

Hey, Phillips, and Parsons[4] give results at 64 megacycles directly in units of radiation per unit area per unit solid angle per frequency interval and in no other terms. The apparent temperature is then obtained from formula (12).

Jansky's measurements were not initially made on an absolute basis, but one of his later papers[18] enables us to

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18. Jansky I.R.E. 25, 1517 (1937).

obtain a fair value for absolute radiation power. Figures 3 and 5 of this paper give the noise power at the antenna terminals for two different antenna orientations as a function of time. The maxima of Figure 3 rise consistently to approximately 52.5 db below one micromicrowatt. Using the relationship discussed above $P = kT\Delta v$, the power $10^{-15.25}$ watts with a band width Δv = 1586 cycles measured by Jansky corresponds to a temperature of 26,000°. However, Harper[19] gives a value 3.5 db for the power lost in the ground and antenna for an antenna of the same type used by Jansky. This raises the apparent temperature to 58,000°. In addition, the noise plotted against time in Jansky's figure 3 is for an antenna direction which does not give maximum noise. The measurements of figure 3, showing maxima at about 5 AM in January, 1937, for an antenna pointed N 50°8'E, correspond to this same direction at about 1 PM in the curves shown in his earlier paper[20] for September, 1932. These latter curves showing radiation as a function of direction throughout the day, show peaks from 3 PM to 9 PM which are on the average 2 db higher than those at 1 PM corresponding to the January, 1937, measurements. Thus, assuming the radiation intensity stayed constant during the five intervening years, the apparent temperature must be at least 92,000° at Jansky's 18 mc frequency. Several other corrections may be applied, most of which would increase the apparent temperature. They are difficult to estimate, however, and are probably not large. We shall take the radiation temperature measured by Jansky as 100,000°. This figure may well be too low, but can hardly be more than 2 db too high.

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19. Harper, Rhombic Antenna Design. Pg. 58 (Van Nostrand, 1941).
20. Jansky, I.R.E. 23, 1158 (1935).

The data of Friis and Feldman[21] (Table VII of their paper) allow one to obtain the ratio of extraterrestrial radio noise at 9.5 M.C. using a narrow-beam antenna to "thermal" noise when the antenna is replaced by a terminating resistance. The result is a ratio of 15.4 db maximum and 9.4 db minimum. Feldman informs the author that the so-called "thermal" noise of this paper was actually between 3 and 5 db above the theoretical thermal noise level 2 kT_r, where T_r is the temperature of the receiver or approximately 300°K. The antennae used were of the same type as that used by Jansky, so that 3.5 db may be assumed lost in receiving. Thus the maximum noise from extraterrestrial sources corresponds to a temperature approximately $2T_r \times 10^{2.29} = 120,000°$. A single measurement is given at 18.6 mc, the temperature computed from it being 60,000°. Although this is not a maximum value, it substantiates Jansky's 100,000° result at approximately this frequency. The data of Friis and Feldman were taken incidentally to the study of an antenna system and consequently are sketchy. The direction from which noise was received is not well known since the antenna had a number of lobes whose direction could be varied over a considerable angle. The results do show, however, that the apparent temperature at 9.5 mc is of the same order as that at 18 mc, both being extremely high.

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21. Friis and Feldman, I.R.E. 25, 841 (1937).

Of course the high temperatures obtained at low frequencies cannot be fitted with any assumption involving electron temperatures near 10,000° as is generally supposed. The high frequency results, as shown in Table 1 may be fitted with T = 10,000°. In order to fit the low frequency data electron temperature near 150,000° must be assumed. This also fits the high-frequency measurements, giving a somewhat better fit for the 64 mc data as shown in the table. Great consistency between the data cannot be expected, however, because of experimental errors and because most of the temperatures measured are averaged over different antenna beams rather than being the actual maxima for an infinitesimal beam width. Both temperatures may be said to give a perfectly satisfactory fit for the high frequencies.

It appears rather difficult to avoid a conclusion from the radio data that interstellar electrons have temperatures of the order of 100,000°. If one supposes that some mechanism other than these electrons is responsible for the radio-frequency radiation, and that interstellar space is actually filled with electrons of density 1 per c.c. and temperature 10,000°, then formula (3) gives an attenuation of e^{-1} for radiation of 9.5 mc frequency in a distance of 500 light years. One must, then, look for a source of this radiation within a relatively short distance from the earth. Again, this source must produce radiation whose intensity increases rapidly with decreasing frequency, since the radiation energy received is approximately independent of frequency over a considerable range although the absorption increases as $\frac{1}{\nu^2}$. Greenstein, Henyey, and Keenan[17] have pointed out a difficulty in attributing the source of this radiation to stars as suggested by Pawsey, Payne-Scott, and McCready.[22] This same difficulty appears to prevent any explanation involving sources associated with the stars if our sun is to be regarded as a typical star. The high temperatures indicated by radio data may be associated with the high temperature of the sun's corona indicated by Edlen[23] and supports the idea that the high energy region of stellar spectra may correspond to much higher temperatures than would be judged from the optical region.

Correlation of the variation of radiation intensity with direction and the dimensions and extent of our galaxy has not been attempted here. It appears to be fruitful and has received some attention from Reber and from Hey, Phillips, and Parsons. It should be pointed out that the radiation maxima for all the measurements quoted were found in the direction where maximum radiation is to be expected with the exception of the data at 9.5 megacycles. In this case the direction from which radiation was detected is somewhat uncertain, and the measurement may not correspond to a true maximum.

Radiation from the Sun

Various authors have reported considerably more radiation from the sun than can be accounted for by black-body

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22. Pawsey, Payne-Scott, and McCready, Nature 157, 158 (1946).
23. Hunter, Report on Prog. in Phys., Phys. Soc. 9, 101 (1942).

Edlen, Nature, 9th March 1946, Vol 157, No 3984, p 297 radiation of the sun itself. The data available seem to indicate two types of excess radiation. First there is a very large excess radiation associated with sun-spot activity as shown by Hey[24] and others[22] which is quite variable in time. In addition there is a smaller amount at higher frequencies which is quite constant in time. Southworth[25] reports three times too much radiation at $\nu \simeq 3 \times 10^9$ and $\nu \simeq 10^{10}$. He finds only one-third of the expected radiation at $\nu \simeq 2.4 \times 10^{10}$, but suggests that this is because of a very narrow antenna beam and considerable refraction of the radio waves in the atmosphere. Dicke[26] reports 1.7 times the expected radiation at $\nu = 2.4 \times 10^{10}$. A possible source of this excess radiation is the ionized gas of the sun's corona. According to formula (3) the absorption coefficient for the sun's corona assuming ionized hydrogen gas at 10^6 degrees K would be $2.5 \times 10^{-31} n^2$ at this frequency.[23]

Dicke and Beringer[26] report that measurements at $\nu = 2.4 \times 10^{10}$ during the partial eclipse of July 9, 1945, show that the apparent diameter of the sun is not more than a few percent larger than its optical diameter. If this is so, only the portion of the sun's atmosphere within this distance can be dense enough to emit radiation of this frequency. Their results

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24. Hey, Nature 157, 47 (1946).
25. Reference 14. Also see erratum Jl. Franklin Inst. 241, 167 (1946).
26. Dicke and Beringer, Astrophys. J., 103, 375 (1946).

can be explained roughly by assuming $n \geq 8 \times 10^9$ close to the sun so that γ times radius of sun ≥ 1, and $n < 8 \times 10^9$ for larger distances.

At lower frequencies, the apparent diameter of the sun may be appreciably greater than its optical diameter. Southworth's results indicate such a possibility. Reber[2] gives a record of solar radiation at $\nu = 160 \times 10^6$. Analysis of this record shows that the sun was emitting approximately 150 times more radiation than would be expected from its optical temperature and size. The sun's width appeared to be 3°, after subtracting his antenna beam width from the record shown. This width is uncertain, however, because of the possibility that the beam width has been underestimated as pointed out above. Radiation at $\nu = 160 \times 10^6$ may be expected from the corona out to distances where n falls below about 5×10^8.

estimates of 11-2-96 ? show 300 times.

480 mc data ?

Summary

By way of summary, it may be said that radiation from interstellar gas explains very well the observed radio radiation from the Milky Way if the density of electron gas is near one per c.c. and its temperature 100,000-200,000 degrees K. It appears difficult to explain such radiation assuming the generally accepted conditions of density one per c.c. and temperature near

10,000°K. The rather meager radio data on the sun's radiation at high radio frequencies suggest a similar radiation process in the sun's corona.

Acknowledgement

This paper has benefited from information and comment generously supplied by many of the experimenters in this field. That they have supplied much essential unpublished information will be obvious to any reader of the above.