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79. CONDITIONS OF ESCAPE OF RADIO-FREQUENCY ENERGY FROM THE SUN AND THE STARS

(*Nature*, **158,** 549, 1946)

In several communications in *Nature*[1,2,3,4] and elsewhere, various British, Australian and New Zealand workers have described experiments carried out during the War which prove conclusively that during times of solar disturbance there are large outbursts of radio-frequency energy from the sun. The wave-lengths measured vary from 1·5 metres to 30 metres (10 Mc. to 200 Mc.). On a rough estimate, the intensity of emission appears to be, as Appleton[1] has shown, 10^4 times the value calculated from the black-body formula taking T=6,000°K. If we assume that the radiation proceeds only from the active areas, as appears to be corroborated by the experiments now in progress at the Cavendish Laboratory, Cambridge[3], the emissivity of these regions for the range mentioned is increased nearly 10^7-10^8 times the blackbody radiation.

There are certain difficulties in the escape of these radiations from the sun to which attention may be directed. It has been found that the quiescent sun has, like the earth, a magnetic field of the order of 50 gauss, but the spots show a field of much higher range, from 100 gauss in the case of tiny spots to 4,000 gauss for the largest ones[5]. If the radio waves are generated anywhere within the outer layers of the sun, then they must follow the physical laws of electro-magnetism. According to the magneto-ionic theory of Appleton, an electromagnetic wave of frequency f, generated anywhere on the earth's surface, can escape vertically from the earth only when the frequency of the waves exceeds certain limits, depending upon the maximum electron concentration above. The exact mathematical relations are

$$f_0^2 > \frac{4\pi Ne^2}{m} > 8{\cdot}0 \times 10^7 . N.$$

$$f_e(f_e + f_h) > \frac{4\pi Ne^2}{m} > 8{\cdot}0 \times 10^7 . N.$$

Here N is maximum number of electrons per c.c. in the ionosphere, f_o is frequency of the *o*-wave, f_e is frequency of the two extraordinary waves, f_h the characteristic gyro-frequency of the electrons under the total field H, $f_h = eH/4\pi$ cm. $=1{\cdot}32\ H$ Mc. These conditions set a lower limit to the frequency of the radiations which can escape from the earth, and their validity has been verified by innumerable experiments.

If we apply these conditions to the sun, and also to the stars, we find at once that severe physical conditions have to be imposed on the emission of radio-waves from these bodies. Taking first the *o*-wave, we should have

$$N < 1{\cdot}25 \times 10^{-8} . f^2$$
$$< 1{\cdot}25 \times 10^6 \text{ for } f = 10 \text{ Mc.}$$
$$< 5 \times 10^2 \text{ for } f = 200 \text{ Mc.}$$

The concentration of electrons in the different layers of the sun has been found by well-tried astrophysical methods[6] to have the mean values of 10^{13} per c.c. for the reversing layer, 4×10^{11} per c.c. for the mean chromosphere, and 4×10^8 per c.c. for the base of the inner corona. It is, therefore, obvious that *o*-radiations of radio-frequency range which we obtain from the sun cannot have their origin either in the reversing layer or the chromosphere, but only in the corona, and that also progressively in the outer layers as the wave-length is increased. But the corona has been shown to be a purely 'electron atmosphere' without any heavier atomic particles, excepting very small concentrations of heavily ionized Fe, Ni and Ca, which produce the coronal lines. The mechanism of origin contemplated by Greenstein, Henyey and Keenan[7] which ascribes the radio-waves to recombination between protons and electrons therefore appears to fall to the ground in the case of the sun.

The e-waves. For the *e*-waves, the value of f_h, is decisive, and this varies from 66 Mc. for the quiescent sun to roughly 4,000 Mc. for the spot, taking H=3,000. These are frequencies of an order which are not contemplated in Appleton's theory, but a little work shows that whatever has been said regarding the *o*-wave also applies to *that* *e*-wave which corresponds to the condition $f_e\ (f_e - f_h) > 8{\cdot}10^7 \times N$ with greater emphasis. In fact, this wave cannot escape unless f_e has very high values, >66 Mc. The *e*-wave corresponds to the condition $f_e\ (f_e + f_h) > 8\times10^7 N$.

The possibility of reception of this wave on the earth has generally been ignored by European and American workers, but it has been obtained distinctly on several occasions by Toshniwal[8] at Allahabad, and his findings have been confirmed by Leiv Harang[9]. Recently, Saha and B. K. Banerjea[10] have shown that any radio-wave generated on the earth would be decomposed into three waves as in inverse Zeemann effect, the *p*-component corresponding to the *o*-wave, and the *S*-components to the *e*-waves. If this deduction be accepted, we at once see that for the spots, the *e*-wave of this type has a far greater probability of escape; for now we should have

$$\mathcal{N} < 1{\cdot}25 \times 10^8 f_e(f_e+f_h)$$
$$< 1{\cdot}25 \times 10^8 f_e f_h, \text{ taking } f_h \gg f_e$$
$$< 5 \times 10^8 \text{ for 10 Mc. waves, and } < 10^{10} \text{ for 200 Mc. waves;}$$

taking $f_h = 4{,}000$ Mc., corresponding to the field-strength of 3,000 gauss. For a quiescent sun, the figures are $\mathcal{N} < 8 \times 10^6$ and $1{\cdot}4 \times 10^8$ respectively. Hence the probability of escape of these waves from the quiescent sun continues to be very small, if the wave originates in the deeper layers. For larger spots, the field generally increases and has been known to reach values as high as 4,000 gauss.

From these arguments, it is fair to draw the conclusion that the large spots are just the regions whence the *e*-waves of the frequency range 10-200 Mc. can escape. The value of the fields given above corresponds to the level where the atomic lines originate, but Chapman[11] thinks that fields might increase to even 10,000 gauss in the deeper layers. If this be true, the *e*-waves can originate even from much deeper layers. Further, it is well known that the spot is a region of far lower temperature, and the electron concentration in the spot is much lower than on the general surface of the sun; this circumstance also helps the escape of the *e*-waves.

If these considerations be on the right line, the radio-waves received on the earth when a big spot is in the centre of the sun's disk should be circularly polarized, and its sense of polarization will be determined by the sign of the field.

These considerations apply equally well to the stars composing the Milky Way region, from which waves in the metre range have been observed[3]. They cannot be emitted from the surface of the hotter stars, but from cooler stars of *G*-, *K*- and *M*-type, and probably the escape of the radiation is facilitated by the development of spots in these stars, analogous to the case of the sun. The difficulties of the dilution factor pointed out by Greenstein *et al.*[7] are therefore eased to a large extent, as, according to Dunham[12], the disk area covered by *K*- and *M*-stars is nearly 10^4 times that of *B*-stars.

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2 Hey, Phillips, Parsons, *Nature*, **157**, 297 (1946).
3 Hey, *Nature*, **157**, 47 (1946).
4 Pawsey, Payne-Scott, and McCready, *Nature*, **157**, 158 (1946).
5 Nicholson, *Pub. Astro. Soc. Pacific*, **45**, 51 (1933).
6 See for reference, Unsöld, "Sternatmosphare", 82, 436, 440.
7 Greenstein, Henyey, Keenan, *Nature*, **157**, 806 (1946).
8 Toshniwal, *Nature*, **135**, 471 (1935).
9 Harang, *Terr. Mag.*, **41**, 143 (1936).
10 Saha and Banerjea, *Ind. J. Phys.*, **19**, 159 (1945).
11 Chapman, *Nature*, **124**, 19 (1929).
12 Dunham, *Proc. Amer. Phil. Soc.*, **81**, 277 (1939).
13 I am indebted to Dr. J. A. Ratcliffe for showing me these experiments during my recent visit to Cambridge.

80. ORIGIN OF RADIO-WAVES FROM THE SUN AND THE STARS

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It has been shown in a previous communication[1] that radio-waves of metre range cannot escape from the quiescent sun unless they originate in the corona, where the electron concentration falls to 10^6-10^8 per c.c. This seems to me to invalidate, at least in the case of the sun, the free free transition theory of the electron in the field of the proton, put forward by Henyey and Keenan[2] to explain the origin of 1-metre waves from regions of the Milky Way. For the corona is a purely 'electron atmosphere', where H-ions cannot exist in any considerable quantity without violating the laws of physics. Pawsey, Payne-Scott and McCready[3] do not consider it likely that these radiations can originate in any atomic or molecular process, but they suggest an origin in gross electrical disturbances, analogous to thunderstorms on the earth. Greenstein, Henyey and Keenan[4] in a note in *Nature* concede that the 1-metre waves emitted from the sun have probably a different origin than in the free free transitions of the electron in the field of the proton.

The object of the present note is to point out that the resources of atomic and molecular processes are not exhausted by the failure of the free free transition process. We have still another group of atomic (or rather nuclear) processes, which can give rise to the radio-waves emitted by the sun and the stars; and these processes are actually stimulated by strong magnetic fields of the type which are characteristic of an active sun. This is the process of excitation by a strong magnetic field of the energy-levels of the nuclei of atoms and molecules, which has been so beautifully demonstrated by the works of Rabi and his school, just before the War[5]. A brief description of the process is given here with the view of bringing out its potentiality for the explanation of the extremely interesting phenomenon of emission of radio-waves by stellar bodies.