escape; for now we should have

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

taking $f_h = 4{,}000$ Mc., corresponding to the field-strength of 3,000 gauss. For a quiescent sun, the figures are $N < 8 \times 10^6$ 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.

University College of Science,
Calcutta.
Aug. 30.

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3 Hey, *Nature*, **157**, 47 (1946).
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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.

The nuclei of many atoms, for example, H^1, Li^7, N^{14}, Al^{27}, Na^{23}, Mg^{25} (mostly isotopes with odd massnumber, D^2, Li^6, B^{10}, N^{10} being exceptions), possess spin, and finite magnetic moment of the order of $eh/4\pi Mc$, the so-called protonic magnetic moment, though actually the proton has a magnetic moment which is 2·7 times higher. In the absence of a magnetic field, the electron-cloud in the outer incomplete shells of the atom or the molecule react on the nucleus, and give rise to hyperfine structure of spectral lines. As a typical and well-investigated case let us take Na^{23}.

This nucleus has been shown to have a spin of 3/2 and a magnetic moment of 2·515 ($eh/4\pi Mc$ being taken as unit). In the normal state, the outermost 3s-electron, which is in the $^2s_{\frac{1}{2}}$-state, causes a fine-structure of nuclear levels, charatderized by the hfs-quantum number $f=|i+j|$, where i is nuclear quantum number, j is inner quantum number of optical level. For normal Na^{23}, $f=|\frac{3}{2}+\frac{1}{2}|=2, 1$. The energy difference between the two nuclear levels has been very accurately measured by optical methods, and found to have the value 0·0592 cm.$^{-1}$ in frequency units. This has been confirmed independently[6].

Normal sodium atoms, say those contained in a sodium lamp, will have some nuclei in the stage $f=2$, some in $f=1$, and those in the state $f=2$ are expected to emit spontaneously waves corresponding to the energy difference $\triangle\nu=0{\cdot}0592$ cm.$^{-1}$, $\lambda=17{\cdot}15$ cm., 1,773 Mc., the balance between the two states being restored by thermal exchange; but normally such transitions will be extremely rare. We can scarcely expect emission of a single quantum from an excited nuclear level in 10^5 years.

But the conditions are entirely changed, as has been shown by Rabi and his co-workers, when the atoms are placed in a strong magnetic field, which is being crossed at right angles by a much smaller, but rapidly varying field, its period being comparable to those of the emitted radiation but not necessarily equal to these. What happens is roughly as follows: under the action of the strong magnetic field, the atom takes up various orientations as in a Stern-Gerlach experiment, the energies of the orientations being as given below (formulae 1 and 2). The varying field causes these orientations to change rapidly, and in this process, radio-frequency waves are emitted. The energy values of the different orientations, however, change considerably with the field, but Rabi has calculated them from an extension of the theory of the Paschen—Back effect. The formulae for Na^{23} are quoted:

Na^{23}: Nuclear spin $i=3/2, f=2, 1$.

m=magnetic quantum number

$=2, 1, 0, -1, -2$ for $f=2$

$=1, 0, -1$ for $f=1$.

ν_{2m}=energy in frequency units of a nucleus with $f=2$ having the orientation 'm':

$$=-\frac{\triangle\nu}{8}+g(i)\,\mu_B H.m+\frac{\triangle\nu}{2}(1+mx+x^2)^{1/2}. \qquad (1)$$

This holds for $m=1, 0, -1$; for $m=2$, the last terms has the value $\frac{\triangle\nu(1+x)}{2}$, for $m=-2$, the value $\frac{\triangle\nu}{2}(1-x)$.

ν_{1m}=energy in frequency units of a nucleus with $f=1$ having the orientation 'm':

$$=-\frac{\triangle\nu}{8}+g(i)\mu_B.H.m-\frac{\triangle\nu}{2}(1+mx+x^2)^{1/2}. \qquad (2)$$

μ_B=Bohr-magnetron, $g(i)$=Lande factor for nuclear magnetism $=\frac{m}{M}\mu_n/i$, where μ_n is the nuclear magnetic moment in terms of $eh/4\pi Mc$ as unit.

$\triangle\nu$=separation between the two states in the absence of a magnetic field.

The number $x=\frac{\{g(j)-g(i)\}\mu_B H}{h\triangle\nu}=\frac{2\mu_B H}{h\triangle\nu}=\frac{H}{660}$ for Na^{23}.

Curves of ν-values will be found in *Phys. Rev.*, 57,769.

The transitions fall in two classes. One set, mostly consisting of those corresponding to $\triangle f=0$, gives ν-values which vary from 0 at vanishing fields to the limiting value of $\triangle\nu/4$ for large fields. For a field of 660 gauss, the wavelengths of the lines emitted are grouped round 1·36 metres, whereas for smaller fields, say 100 gauss, they may be as high as 4 metres. When the field is very large, the emission is grouped round $4\times17{\cdot}15=68{\cdot}60$ cm.

The second set, mostly consisting of radiations corresponding to $\triangle f=1$, gives ν-values from $\triangle\nu$ to $x\triangle\nu$; these may give rise to centimetre waves; in fact, for $H=10{,}000$ gauss, the emission is grouped round 1·1 cm.

These relations have indeed not yet been verified in emission, but in some ingenious absorption experiments by Rabi and his co-workers for Na^{23}, Li^6, Li^7, Cs^{133}, K^{41}; but there seems to be no reason why it should not be possible to design emission experiments, for example, by putting a sodium lamp in a strong magnetic field, which is then crossed by a feeble oscillating magnetic field at right angles. Such sodium lamp ought to give out strong radio-waves of both metre and centimetre range. It is desirable to carry out such experiments in view of the prospect which they hold out of throwing light on the all-important question of stimulation of transitions.

What we have said with respect to Na^{23} will also apply to the nuclei H, Li^6 and Li^7, B^{10}, B^{11}, N^{14}, Na^{23}, Al^{27}, and other nuclei which possess spin and magnetic moment, and therefore when forming part of an atom or molecule can exist in several well-defined quantized states produced by the electron cloud. The details of calculations will, however, widely differ, and cannot be given in this short communication; but as in the case of Na^{23}, they will give rise to both metre and centimetre waves.

The most important part in the sun and the stars will, however, be played, not by Na, but by hydrogen, because this forms, according to well-verified astrophysical arguments, 95 per cent of total number of atoms in the atmosphere of the sun; in the stars, also, hydrogen forms in the majority of cases more than 90 per cent of the atmosphere. Na was chosen simply to illustrate the phenomenon. In the spots, on account of lower temperature, the hydrides CH, MgH and SiH (and possibly H_2) are formed in great abundance, and their spectra form characteristic features of spots, but the greater proportion remains in the atomic state. For the H-atom, $\triangle\nu$ cannot be obtained from hyperfine structure experiments, but it has been calculated to have the value of $0{\cdot}0163\ \mu_p = 0{\cdot}0474$ cm.$^{-1}$, $\lambda=21$ cm., $x=H/500$, and calculation shows that both centimetre and metre waves can be emitted by the H-atom, corresponding to $\triangle f=0$, $\triangle f=1$. But in the case of hydrides, N_2, CN, no experimental data or theoretical calculations are yet available; but it can be surmised that the characteristic radio-frequency waves would be much longer.

In addition to waves arising out of nuclear transitions, the rotational states of the molecules have also been shown by Rabi and his pupils to be capable of radio-frequency transitions in magnetic fields.

We consider next the possibility of nuclear emission of radio-waves of both centimetre and metre range from the sun and the stars. It now appears extremely probable that the radio-waves observed can be emitted only from the sunspots. The spots show in the centre of the umbra large magnetic fields which vary with the size of the spot[7], and may reach values as high as 4,500 gauss. The direction of the field is axial (that is, perpendicular to the surface of the sun) in the centre of the umbra, but it becomes inclined to the solar radius as we proceed towards the penumbra, and also diminishes in value. The values of the fields are exactly such as will promote the emission of centimetre and metre waves according to the schemes given above, and the intensity of emission will be large enough if we can postulate the existence of a small cross-field, having frequencies of the same magnitude as those of the radio-waves. It is not improbable from what we know of the physical nature of sunspots that such variable fields do actually exist, and may partly be provided by the fields of the 'ordinary'-waves, and the 'extraordinary'-waves corresponding to the condition $f(f-f_h) > \frac{4\pi Ne^2}{m}$ coming from below, which may, however, find it impossible to penetrate the electron barrier above (see ref. 1).

These speculations, though far from being established on a sure basis, are given on account of their promise of being able to throw light on a series of extremely interesting phenomena, the origin of which has so far appeared to be wrapped in mystery; the moment is also opportune because experiments on the subject are being undertaken all over the world. If the speculations are on the right lines, it appears that sunspots would also strongly emit radio-waves of the centimetre range. I am not aware if any such observation has yet been made. Further, the emission of centimetre waves by the stars of the Milky Way probably indicates the development of spots in these stars, which should belong to the G, K and M classes. But no spectroscopic observation in verification of such a hypothesis is known to me, and from the nature of things it appears extremely unlikely that any such observation is possible, unless the spots in these stars possess gigantic proportions.

1 *Nature*, **158**, 549 (1946).
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3 Pawsey, Payne-Scott and McCready, *Nature*, **157**, 158 (1946).
4 Greenstein, Henyey and Keenan, *Nature*, **157**, 806 (1946).
5 See, for example, Kusch, Millman and Rabi, "Radio-frequency Spectra of Atoms and Molecules", *Phys. Rev.*, **57**, 765.
6 *Phys. Rev.*, **58**, 441.
7 Nicholson, *Pub. Astro. Soc. Pacific*, **45**, 51 (1933).