ON MARIS AND HULBURT'S ULTRAVIOLET LIGHT THEORY OF AURORÆ AND MAGNETIC STORMS

By TA-YOU WU

(Department of Physics, National University of Peking, and Institute of Astronomy, Academia Sinica, Kun-ming, China)

Received October 26, 1943

(Communicated by Sir C. V. Raman, KT., F.R.S., N.L.)

IN a series of papers, Maris and Hulburt have developed an ultraviolet light theory of auroræ and magnetic storms.[1] The theory is not subject to the difficulty pointed out by Schuster and by Lindemann against the corpuscular theory, and is claimed to give a satisfactory explanation of the concentration of the auroræ in the region of high latitudes, the diurnal variations of magnetic storms, etc. The theory is based on the following assumptions: (1) The $\sim 10^{16}$ atoms or molecules (called simply particles here) in a column of unit cross-section above $\sim$ 450 km. bounce up and down with exceedingly long free paths and make $\sim 10^{14}$ collisions per second at the 450 km. level. The particles at this level are excited to high energy states or ionized by solar radiations. In collisions of the second kind with these excited particles or in collisions with recombining particles, the particles from above receive energies corresponding to velocities as high as 10 km./sec. It is assumed that some 10^8 of these 10^{14} collisions are of this nature. The particles will reach some 40,000–80,000 km. in 3 to 6 hours. (2) These high flying particles are ionized by solar radiations in 3 to 6 hours and, being now electrically charged, come down in spirals around the lines of force of the earth's magnetic field. These ions coming down into the lower atmosphere produce the auroræ, etc.

This theory has been examined by Chapman and its consequences have been compared with the observed facts.[2] Mitra and Banerjee have made some calculations on the basis of this theory and obtained somewhat different values for the number of particles sent up per second and the time

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[1] H. B. Maris and E. O. Hulburt, *Phys. Rev.*, 1929, **33**, 412; Hulburt, *ibid.*, 1929, **34**, 344; 1930, **36**, 1560; *Rev. Mod. Phys.*, 1937, **9**, 44.

[2] S. Chapman, *Monthly Notices, Roy. Astro. Soc. Geophys. Supp.*, 1930, **2**, 296; *Terr. Mag.*, 1938, **43**, 77. These papers are not available to the writer who comes across reference to the first in the articles by Hewson, *Rev. Mod. Phys.*, 1937, **9**, 430, and Hulburt, *Phys. Rev.*, 1930, **36**, 1560, to the second in *Science Abstracts*, No. 2814, 1938.

taken for the ionization of these particles.[3] The purpose of this note is to examine more closely the fundamental processes assumed by Maris and Hulburt and the calculations of Mitra and Banerjee.

Granting that the distribution of particle density with height is what the original authors assume, we can show that the number of particles receiving a high velocity by the assumed mechanism is extremely small. Consider first the possibility of a particle acquiring a high velocity by a collision of the second kind with an excited atom or molecule at the 450 km. level. The ratio of the concentrations of particles in an excited state k and in the ground state i may be expected to differ greatly from the Boltzmann factor on account of the low pressure and hence the scarcity of collisions in the upper atmosphere. To obtain the relative populations it would be necessary to treat the problem as one of radiative equilibrium in diluted temperature radiation according to the theory of cycles of Rosseland. For the consideration of the order of magnitude only, we may simplify the problem by considering only the state i, the state k and the continuum c so that we have

$$N_i B\overset{k}{\underset{i}{\uparrow}} \rho(\nu) + N' \int_0^\infty v\, Q(v) N_e(v)\, dv = N_k A\overset{k}{\underset{i}{\downarrow}} + N_k \int_{\nu_0}^\infty \frac{\tau(\nu)}{h\nu} I(\nu)\, d\nu, \qquad (1)$$

where N_i, N_k, N', $N_e(v)\,dv$ are the concentrations of particles in the states i, k and the ionized state, and of electrons having velocities between v and $v + dv$, respectively, $Q(v)$ is the cross-section for electron capture by the ion into the state k, $\tau(\nu)$ the cross-section for photo-ionization of the state k, $I(\nu)$ the intensity of solar radiation of frequency ν, and $B\overset{k}{\underset{i}{\uparrow}}$ and $A\overset{k}{\underset{i}{\downarrow}}$ are the Einstein coefficients of absorption and spontaneous emission respectively. It can readily be verified that the second term of the right-hand side of (1) is very small compared with the first, and for electron capture cross-section of the order 10^{-21} cm.[2] and total electron density less than 10^6/c.c., the second term on the left of (1) is small compared with the first so that approximately

$$N_k/N_i = (g_k/g_i)\, B\overset{k}{\underset{i}{\downarrow}} \Big/ A\overset{k}{\underset{i}{\downarrow}} = \frac{g_k}{g_i} \frac{c^3}{8\pi h\nu^3} \rho(\nu), \qquad (2)$$

where $\rho(\nu)$ is the radiation energy density at frequency ν, $h\nu = E_k - E_i$ and the g's are the statistical weights. ρ can be taken to be W times that of a black body at T = 6000° K. where W is the dilution factor and is $\sim 5 \times 10^{-6}$. For $E_k - E_i = 13$ volts so that one half of it when transferred to a colliding particle of the mass of an oxygen atom may give it a velocity $\sim$ 9 km./sec.,

[3] S. K. Mitra and A. K. Banerjee, *Indian J. Phys.*, 1939, 13, 107.

the above ratio N_k/N_i is $\sim 10^{-16} g_k/g_i$. Thus of the 10^{14} collisions between the particles from above and those below, only $\sim 1/10^2$ of a collision takes place with an excited atom or molecule. Furthermore, the probability of energy transfer from an excited atom or molecule to a heavy particle is known to be very small, probably of the order of $10^{-3} - 10^{-1}$ per collision, when the energy must go into the kinetic energy of translation of the heavy particle. This small probability is due to the great disparity in the masses of the electron and the heavy particle. Hence of the 10^{14} collisions, only $10^{-5} - 10^{-3}$ of a collision, not 10^8 as Maris and Hulburt assumed, will result in imparting a high velocity to the particle from above.

Consider next the plausibility of a particle from above acquiring a high velocity on collision with recombining particles below. Now this is a three-body process and as such the probability is extremely small on account of the low pressure in the upper atmosphere. This probability can be expressed in terms of a cross-section of the recombination for unit concentration of the third body. On making an optimum assumption that the probability of the energy transfer in a given collision is $\sim 1/100$, this cross-section for unit concentration of the third body is $\sim 10^{-42}$ cm^6.[4] At a height where the concentrations of the recombining particles and of the third body are all of the order 10^{10}/c.c., the number of 3-body collisions is about 10^{-7} per second per c.c. Thus the number of particles acquiring a high velocity from recombining particles is too small to play any role in producing auroræ.

Consider now the calculations of Mitra and Banerjee for the number of particles sent up in collisions of the second kind between an atom and an oxygen atom in the metastable state ^1S formed by the capture of an electron by an oxygen ion O^+ produced by photo-ionization. The probability of ionization is given, as in (1), by

$$w = \int_{\nu_0}^{\infty} \frac{\tau(\nu)}{h\nu} I(\nu)\, d\nu \tag{3}$$

where the atomic absorption coefficient $\tau(\nu)$ is $\sim 1 \cdot 4 \times 10^{-17}$ according to Bates, Buckingham, Massey and Unwin.[5] One has then $w \sim 1 \times 10^{-8}$ so that of the 10^{16} particles in a column of unit cross-section above $\sim$ 770 km., about 1×10^{-8} are ionized per second. The number of recombinations forming $O(^1S)$ in the column per second is given by $q = \alpha N_+ N_- L$ where α is the recombination coefficient for radiative process, N_+, N_- are the

[4] *Cf.* H. S. W. Massey, *Negative Ions*, Cambridge Univ. Press, 1938.

[5] Bates, Buckingham, Massey and Unwin, *Proc. Roy. Soc.*, 1939, **A 170**, 322.

concentrations of O^+ and electrons and L is the height of the column such that $N_+ L$ = total number of O^+ in the column. Now Mitra and Banerjee obtained a value 10^5 for q by putting $q = \alpha\ n_+ n_-$ where n_+, n_- are the numbers of O^+ and electrons produced in the column per second, a procedure which is obviously incorrect. To obtain an estimate of q, we need, not the numbers of O^+ and electrons produced per second in the column, but the concentrations and the total numbers present at a certain moment. The total number of O^+ in the column after irradiation by solar radiations for some 10^4 seconds (a few hours) is of the order 10^{12}. This number of O^+ and hence also of electrons must be spread over a great height so that the electron density N_- is probably of the order 10^3/c.c. (it cannot be much greater, for otherwise it would have been revealed by observations on the reflection of radio waves). As α is of the order 10^{-13} according to Bates *et al.*,[5] one finds for q a value $\sim 10^2$ per second. As the lifetime of the state ^1S of OI is 0·5 second and as the collision frequency at the level 800–900 km. is about one in 75 seconds, these 10^2 O (^1S) atoms make about 1 collision per second with other atoms. Of this only a fraction, say γ, will be of the second kind, where γ is the efficiency of energy transfer and is certainly less than unity. It is then clear that the process considered by Mitra and Banerjee is inadequate in accounting for the auroræ and magnetic storms. Incidentally it may be pointed out that the 4·2 volts of energy released in the process $^1S \rightarrow {}^3P$ in the oxygen atom will be divided between the two colliding atoms on momentum considerations so that the energy available for shooting the atom is only about 2 volts.

The above considerations also make it clear that no material changes in order of magnitudes of the various quantities will be obtained for the case of an active sun.

Finally, the assumption that the high flying atoms are ionized by solar radiations in 3 to 6 hours is based on the relation

$$E = t\,(I_0 - I) = t\,I_0\,(1 - e^{-\tau}), \qquad (4)$$

where E is the ionization potential of the particle, t is the time in which the particle is ionized, I_0 and I are the intensities of the ionizing radiations before and after traversing a column of unit cross-section and of such height that it contains just one particle, and τ is the atomic absorption coefficient defined by the usual relation $I = I_0\, e^{-N\tau x}$. Mitra and Banerjee employed the relation (4) and found $t = 3 \times 10^3$ hours. Now the above relation for t implies that the atom continues to absorb energy from the radiation beam for a time t until it amounts to the ionization potential E. This is entirely at variance with the basic idea in the quantum theory in which the process is governed entirely by probability considerations. The time t should be given by the relation

$$t = 1/w, \tag{5}$$

where w is the number of transitions per second from the bound state to the continuous state under the action of the radiation field. As ionization can be effected by all radiations with frequency ν greater than the value ν_0 corresponding to E, the total probability of ionization by solar radiations is simply that given by (3) and is of the order 10^{-8} per second. Hence the lifetime of the neutral oxygen atom is $\sim 10^8$ seconds instead of the values assumed by Maris and Hulburt and calculated by Mitra and Banerjee on the basis of (4).

Thus on the above general considerations, it is clear that the assumed physical picture of the processes invoked in the theory of Maris and Hulburt is inadequate for explaining the cause of auroræ and magnetic storms.