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ON THE POSITIVE CHARGE OF THE SUN

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Krat, V. O polozhitel'nom zaryade solntsa. IN: Akademiya nauk SSSR. Doklady, v. 55, no. 3, 1947, 207-210.

The spectroscopic characteristics of the inner corona can be explained only by assuming a high kinetic temperature for the gas mixture comprising it (Ref. 1). The high temperature of the corona explains 1) the high ionization of Fe, Ti, and Ca; 2) the character of excitation of the coronal lines; 3) the absence of all Fraunhofer lines in the continuous spectrum of the corona, with the exception of a strongly diffused group of lines near $\lambda = 3800$ Å; and 4) the absence of hydrogen emission lines in the corona.

Explanations of these phenomena by hypotheses of hard or corpuscular solar radiation emitted from great depths must be rejected as leading to an anomalous excitation of atoms and high ionization in the reversing layer. Elementary computations of the coefficient of internal friction from Kothari's formulas (Ref. 2) show that in the upper layers of the chromosphere elementary streams with a cross section of several hundred meters should be completely destroyed in several seconds, while in the corona (at $T \sim 10^6$) the process requires only millionths of a second. The kinetic energy of turbulent streams should be completely transformed into the thermal energy of particle motion in this process. Moreover, the disintegration of chromospheric ejections rising with velocities of 100 km and more, leading to a temperature of 10^6 degrees, must also be taken into account. In addition to the energy of chromospheric gas stream disintegration, the energy of motions creating nonconservative force fields — — the field of selective radiant pressure and the field of electrostatic solar charge — — must also be added to the thermal energy of the corona. These fields tend to separate particles of different types (with different coefficients of absorption and different charges). This unavoidably leads to an increase of the internal energy of the gas mixture (Ref. 4). Thus, the temperature inversion, beginning at a height of 2000 to 3000 km (Ref. 3) above the photosphere, grows to the region of the inner corona, where it reaches a maximum.

In the region of the corona and even in the chromosphere the mean square velocities of free electrons exceed the escape velocity of particles moving freely away from the sun. In the absence of a positive solar charge all free electrons of the corona would scatter almost instantaneously in the surrounding space. Such a dispersion of electrons, however, would itself create a continuously increasing positive charge on the solar surface, decreasing the effective gravitational force for protons. Beginning from a certain moment, a stationary state should arise in which the increase in charge due to the dispersion of fast electrons is completely compensated for by a decrease in charge due to the dispersion of protons. Disregarding the forces of interaction (quite small under coronal conditions) for fast particles, we can in the first approximation compute the charge of the sun, proceeding from the principle of the stationary state. We may consider that half of the particles arriving at one degree of freedom disperse; i.e., $1/6N(v)$, where $N(v)$ is the number of atoms having velocities in the interval v, $v + dv$ (v exceeds the escape velocity). The escape velocity of a particle from the sun depends upon the effective gravitational force acting on it, i.e.,

$$v_e^2 + 2g_{eff}R_{\odot}. \tag{1}$$

The g_{eff} for protons and electrons is:

$$g_p = g_0 + \frac{e\dot{\phi}}{m_p} \text{ (protons)}, \quad g_e = g_0 - \frac{e\dot{\phi}}{m_e} \text{ (electrons)} \tag{2}$$

where g_0 is the acceleration due to gravity, e is the electron charge, m_p and m_e are the corresponding masses of the proton and electron, and $\dot{\phi}$ is the gradient of the electrostatic field of the sun. We shall consider that the corona consists almost exclusively of hydrogen and that the remaining elements in it play only the role of polluting admixtures.

Disregarding the values of g_0 in comparison with $e\dot{\phi}/m_e$ and replacing $e\dot{\psi}/m_p g_0$ by β, we obtain

$$g_p = g_0\,(1 - \beta), \; g_e = \frac{m_p}{m_c}\, g_0\beta. \tag{3}$$

We shall assume that at the present time the stationary state in which loss of electrons is compensated for by loss of protons has been established. Equating the number of dispersing protons to the number of electrons, we have

$$\int_{v_{p,e}}^{\infty} N_p\,(v)v\;\;dv + \int_{v_{e,e}}^{\infty} N_e\,(v)v\;\;dv\,, \tag{4}$$

where the escape velocities for protons and electrons are represented by $v_{p,e}$ and $v_{e,e}$, respectively. Substituting in place of $N_p(v)$ the expressions corresponding to them in terms of υ and t according to Maxwell's law, replacing all constant coefficients by their numerical values, and integrating with respect to υ, we obtain the following equation:

$$42.9 \frac{1 + 2.30\cdot 10^7 \frac{\beta}{T}}{1 + 2.30\cdot 10^7 \frac{1 - \beta}{T}} = e^{\frac{2.30\cdot 10^7}{T}(1 - 2\beta)} . \quad (5)$$

The following values of β for the case of thermal dissipation can be obtained by the method of successive approximations at different values of T:

$$T = 10^5,\ \beta = 0.508;\quad T = 10^6,\ \beta = 0.6;\ T = 10^7;\ \beta = 1.3.$$

As we see, in the range between $T = 10^6$ and $T = 10^7$, i.e., at a temperature close to that of the corona, β reaches unity. The protons in the solar corona are found to be practically weightless.

Besides thermal dissipation, we shall also examine the dissipation which is the result of radioactive decay and of the disintegration of atoms under impacts of fast particles such as cosmic rays. In both cases there arise streams of fast particles, both positive and negative, leaving the stellar atmosphere. Since electron rays ("$\beta-$ rays") are less restrained by the atmosphere than the heavy positive particles, the nuclear reactions of disintegration can lead to negative corpuscular radiation outweighing the positive radiation. If the number of excess fast electrons in the outer layers of the corona is N_e'/N_e (N is the total number of particles in 1 cm^3), then their velocities will be close to 10^{10} cm. Then in 1 sec $1/6 N_e \cdot 10^{10}$ fast electrons pass through 1 cm^3. Since neither the gravitational nor the electrostatic field of the sun can have an effect on these electrons, the number of positive particles (protons) compensating for the negative corpuscular radiation of the sun must be:

$$\frac{1}{3\sqrt{\pi}} \left(\frac{2kT}{m_p}\right)^{1/2} \left(1 + \frac{m_p\, \upsilon^2{}_{p,e}}{2kT}\right) e^{-\frac{m_p\, \upsilon^2_{p,e}}{2kT}} = \frac{1}{6}\frac{N'_e}{N}\, 10^{10}. \quad (6)$$

We disregard the phenomenon of thermal dissipation here. At $T = 10^6$ we have:

$$(1 + x)\, e^{-x} = A, \quad (7)$$

where $\quad X = 6.05\cdot 10^{-16}\ \upsilon^2_{p,e} = x,\quad A = 0.69\cdot 10^3\ N_e/N. \quad (8)$

At $A = 1$, $x = 0$, we have the case of total equilibrium of protons in the atmosphere. At $A > 1$, x becomes negative, i.e., β becomes greater than one (negative energy of detachment). Only the last case is of interest, since at $A \leq 1$ we are not able to disregard thermal dissipation. At $A > 1$ the least of the values of A that interest us will be of the order of $10^{8} N_e/N$.

The number of fast electrons formed in 1 cm^3 of the corona will be about 10^{-12} of N (the order of the depth of penetration of cosmic rays in the corona is close to 10^9 cm). In other words, only one fast particle is formed in 1 sec in 10^4 cm^3 (the number of particles in the lower layers of the corona is close to 10^8 for 1 cm^3).

The magnitude of the charge $Z_{\odot}$ is apparently equal to the charge, increased β times, of excess protons balancing the gravitational force for one proton on the surface of the sun. Since this number of protons equals 10^{21}, the electrostatic charge is $5 \cdot 10^{11}$ β electrostatic units. The field intensity on the surface of the sun will be equal to $3 \cdot 10^{-8}$ β v/cm.

The velocity of the protons emitted from the solar atmosphere will change according to the principle of conservation of energy:

$$v^2 = v_0^2 + 2G(\beta - 1)\, m_{\odot} \frac{n-1}{nR_{\odot}}, \qquad (9)$$

where n is the distance from the limb of the sun expressed in solar radii, $m_{\odot}$ is the mass of the sun, G is the gravitational constant, and v_0 is the initial velocity. Equation (9) can also be written in the form

$$v^2 = v_0^2 + 0.38 \cdot 10^{16} (\beta - 1) \frac{n-1}{n}. \qquad (10)$$

It is interesting that as early as $\beta \sim 2$ the protons can reach the earth with a velocity of about 600 km/sec.

If we suppose $\beta = 1$, then the relaxation time for the sun (the time in which the mass of the sun is reduced by two times) will be of the order of 10^{12} years. This does not contradict our ideas on the age of the earth and the sun. It must be noted, however, that in general the loss of mass of the star owing to corpuscular radiation is apparently significantly greater than the loss of mass through the loss of radiant energy.

Let us imagine that a cloud of ionized hydrogen atoms is ejected with considerable velocity beyond the limits of the inner corona. The conditions of thermal dissipation for this cloud will be incomparably more favorable than for the sun as a whole, since the force of gravity created by the cloud mass can be disregarded. For this reason the cloud quickly acquires a positive charge. If the quantity of excess protons of the cloud in the first rough approximation is constant and equal to x', then the velocity of the radial motion of the cloud will be expressed by the formula

$$v^2 = v_0^2 + 0.38\cdot 10^{13}(\beta x' - 1). \qquad (11)$$

The acceleration of the cloud will be positive only at $x' > 1/\beta$. The particle velocity distribution within the cloud will no longer be Maxwellian, even when all velocities — — deducting the translational velocity of the cloud — — are thermal velocities. Let us assume in the first approximation that at a sufficient distance from the sun our cloud is spherical with an initial radius R. At a certain distance nR from the center of the cloud, and where $n \gg 1$, the action of the charge will only have the result that all the protons acquire an additional kinetic energy, constant in value for all positive particles with a unit charge. In view of the fact that we may disregard the interaction of sufficiently fast particles, the motion of the cloud particles can be roughly assumed to be uniform and rectilinear. We shall call the sphere of radius nR the sphere of dissipation. The time interval required by protons with a Maxwellian velocity v (mean square velocity) to reach sphere nR, will be called the time of dissipation. If the initial particle velocities are designated in terms of v, then their velocities in absolute values near sphere nR will be

$$v' = \sqrt{v^2 + \Delta}\ , \qquad (12)$$

where Δ is the average increment of the square of the velocity. The velocity distribution will become radial with respect to the center of the cloud. After a time interval t (from the moment of ejection from the nucleus), particles with a velocity in the range v, $v + dv$ will be located on a sphere of radius $r - v't$, and their density will be proportional to $\omega(v)$ (the quantity of particles of a given kind) and inversely proportional to t^2. If $\omega(v)$ follows Maxwell's Law, then the maximal density will at all times be maintained in the cloud nucleus. Taking R = 5000 km and n = 10 mm, we shall at $T = 10^6$ obtain a dissipation time close to 8 minutes, while at $T = 10^2$ the time of dissipation will have already grown to 10 hours.

Thus, only the coldest ejections can survive for a more or less protracted period of time. Therefore, only the slowest ("coldest") particles remain within sphere nR. The outer corona, in which, for the most part, only directed particles move, must to a considerable degree consist of these "cold" particles. It is possible that the Fraunhofer spectrum of the outer corona is created by this cold, slowly scattering, swarm of particles. It must be noted that the relative durability of coronal forms, and especially the correct from of coronal rays, can be explained only by assuming a low kinetic temperature for the particles comprising them. Clusters of "cold" particles (positive and negative) resemble an electric plasma, which may exist a long time when not subjected to rapid dissipation.

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