NEUTRONS AS AN ENERGY SOURCE FOR THE SOLAR CORONA

Jafar Hashemi and R. G. Fowler

Department of Physics, University of Oklahoma, Norman, Oklahoma

It is proposed that heat is transported to the corona through the agency of neutrons originating in the photospheric layer of the sun. A steady state model for the corona has been developed. A flux of neutrons is assumed to reach the base of the corona. The neutrons decay in the corona and release electrons and protons which collide with the coronal gas and distribute their energy. Neutrons are assumed to be produced in the solar photosphere by returning protons which have been unable to escape the solar magnetic field.

There is no satisfactory theory for the source that supplies energy to the solar corona (1). It is not the purpose of this paper to criticize all available qualitative theories, but we should like to mention the following facts that led us to the idea of escaping neutrons as the primary energy source (2).

(A) Since 1959, the search for the solar neutrons has provided positive evidences for the emission of neutrons from the sun. Both experimental and theoretical investigations have shown that neutron eruptions on the sun play a very important role in the physics of the sun itself and should be considered seriously in future solar physics researches.

(B) According to Störmer's theory, the minimum momentum that a charged particle can have in order to be able to leave the sun in the region of the equator is given by

$$\frac{ea}{cR_s^2}(3-2\sqrt{2}) \qquad \text{Eq. 1}$$

where a is the magnetic moment of the sun and R_s is the radius of the sun. Substituting a $\simeq 10^{33}$ gauss cm^3 gives 10^{13} eV/c. This large value of the momentum is inconsistent with the average particle velocity from the sun to earth (350 Km/sec = 800 eV), a fact which suggests that the solar particle emission must be neutral.

(C) Long, stretched-out clouds of matter escaping from the sun with velocity of approximately 700 Km/sec have been observed. Furthermore, at the orbit of earth there is a continuous flux of order 6×10^8 protons/cm^2/sec even for the quiet sun.

Consideration of the above facts suggests that neutral particles are initially emitted from the sun which subsequently acquire their charge in interplanetary space. The most suitable particle for this emission is the neutron. Neutrons decay according to

$$n \rightarrow p + \bar{\nu} + \bar{e} + 0.78 \text{ MeV} \qquad \text{Eq. 2}$$

with a half life of about 13 minutes.

On the average the electrons carry 0.39 MeV. These electrons, after successive collision with the coronal gas, lose their energy and, thus, heat the corona. The average life of the neutron multiplied by the observed velocity of the escaping matter is a length of the size scale of the corona. Decaying as they do exponentially in time, and, therefore, over their path outward, most of the neutrons decay at the base of the corona. This can serve to explain the sudden rise of temperature from chromosphere to corona.

MODEL FOR THE SOLAR CORONA

A steady state model for the solar corona has been developed. A flux of neutrons, protons, and electrons is assumed to reach the base of the corona. It is assumed that the corona is electrically neutral. Conservation of mass, momentum, and energy implies the following equations:

$$\sum_i (\nabla \cdot n_i v_i) = 0 \qquad \text{Eq. 3}$$

$$\sum_i [n_i m_i (n_i \cdot \nabla) n_i + \nabla p_i - \frac{n_i m_i GM}{r^2}] = 0 \qquad \text{Eq. 4}$$

$$\sum_i [\nabla \cdot n_i v_i (\tfrac{1}{2} m_i v_i^2 + w_i - \frac{m_i GM}{r})] + \nabla \cdot \frac{n_3 v_3 E_D}{2} - \epsilon = 0 \qquad \text{Eq. 5}$$

where i = 1,2,3 referring to electron, proton, and neutron, n is the density, v is velocity, m is mass and $w_i = 5/2\ kT_i$. E_D is the decay energy of the neutron and ε is the loss of energy due to conduction and radiation, r is the distance from the center of the sun, M is the mass of the sun and G is gravitational constant.

In order to get an estimate of neutron flux to the base of the corona, total energy reaching the base is equated to the total energy lost by the corona.

$$\sum_i \Big[\tfrac{1}{2} m_i v_i^3 n_i + 5/2\ n_i v_i kT_i + \frac{n_3 v_3 E_D}{2} - \frac{n_i m_i v_i GM}{R_s}\Big] R_s^2 \qquad \text{Eq. 6}$$

$$= \sum_i \Big[\tfrac{1}{2} m_i v_i^3 n_i' + 5/2\ n_i' v_i' kT_i' - \frac{n_i' m_i v_i' GM}{R_e}\Big] R_e^2 + L_R + L_C$$

where R_e is the orbit of earth, R_s is the radius of the sun, L_R and L_C are the total energy lost by the solar corona in the form of radiation and conduction, respectively, and n_i', v_i', T_i' are density, velocity, and temperature at R_e. It is assumed that all neutrons decay in the corona. Substitution of a flux of 6×10^8 protons/cm²/sec at R_e and 10^{13} protons/cm²/sec at R_s and $L_r = 6 \times 10^{27}$ ergs/sec, $L_c = 10^{27}$ ergs/sec leads to

$$n_3 v_3 \simeq 10^{11} \text{ neutrons/cm}^2\text{/sec}.$$

This is the total neutron flux at the base of the corona required to explain the energy of the corona.

ORIGIN OF NEUTRONS FROM THE SUN

Two possibilities suggest themselves for the origin of the neutron flux: either escape of neutrons from the internal thermonuclear reaction zones, or stripping reactions in the photosphere.

The most important reaction that produces neutrons in the solar upper interior is the following:

$$D + D \rightarrow {}^3He + n + 3.25 \text{ MeV} \qquad \text{Eq. 7}$$

From the density and temperature distribution inside the sun and cross-section for the above reaction, we have calculated total neutron production of the sun. The diffusion equation for the neutrons produced in the interior of the sun has been solved, and it was found that most of the neutrons decay before reaching the surface of the sun. Unless the temperature near the surface (at 0.9 R_s) is rather higher than has been supposed, the DD reaction cannot give any contribution to the neutron flux from the sun.

The second possibility is stripping reactions in the photosphere induced by fast charged particles from flares. All but a very few of the particles which are accelerated during a flare will not have enough energy to escape the surface of the sun and be directed downward to the photosphere. The downward flux of the flare-accelerated protons and α particles will interact with the photosphere. Proton-initiated reactions, such as ^{4}He(p, pn)^{3}He, ^{4}He(p, 2pn)^{2}H, ^{4}He(p, 2p2n)^{1}H, ^{4}He(p, pnπ. . .), and ^{14}N(p,n)^{14}O, or α-particle-initiated reactions, such as ^{1}H(α,np)^{3}He, ^{1}H(α,2pn)^{2}H, and ^{1}H(α,2p2n)^{1}H, are possible neutron-producing reactions.

Some of the particles that are accelerated in small flares will remain trapped in the magnetic fields of the flares and will produce neutrons during quiet times.

A neutron which is produced in the photosphere will decay in the corona if its kinetic energy is the order of 10 KeV. (The mean life of the neutron is $\tau = 1010 \pm 25$ sec). Of all possible proton-initiated reactions which produce neutrons in the photosphere, ^{14}N(p,n)^{14}O has the lowest threshhold. The total cross section for this reaction has been measured by Kuan and Risser (3). The threshold of this reaction is reported as 6.345 ± 0.015 MeV. If the proton energy is of the order of the threshold, the average neutron energy is of the order of 10 KeV, which as noted is the energy required for the neutrons to decay in the corona. For the active sun, more energetic protons will be present and can excite both γ rays and additional neutrons.

A rough estimate of the neutrons produced by ^{14}N(p,n)^{14}O in the photosphere can be made as follows:

Let ϕ_0 be the flux of monoenergetic protons which return isotropically to the photosphere and r be the distance (in cm) from the base of the chromosphere towards the center of the sun. The number $d\phi_n$ of neutrons produced in one second in dr at r is

$$d\phi_n = -d\phi = \phi\sigma_1 n_N dr \quad \text{Eq. 8}$$

where σ_1 is the total cross section for $^{14}N(p,n)\,^{14}O$, ϕ is the proton flux at r and n_N is the density of nitrogen. From the model constructed by Allen (4), the following approximate expression for the density distribution in the photosphere is derived

$$n_H = ae^{br} \quad \text{Eq. 9}$$

where n_H is the density of hydrogen, $a = 6 \times 10^{15.3}$, and $b = 8.45 \times 10^{-8}$. The relative cosmic abundance of nitrogen to hydrogen is 10^{-4} (5). Substitution of $n_N = a'e^{br}$ where $a' = 10^{-4}a$ in Eq. (8) and integration leads to:

$$\phi = \phi_o \exp\left[\frac{\sigma_1 a'}{b}(1-e^{br})\right] \quad \text{Eq. 10}$$

The flux of neutrons which is produced by ϕ and reaches the surface of the sun is given by:

$$\Phi_n = \tfrac{1}{2}\int_0^{r_1} \frac{d\phi}{dr} \exp\int_0^{r} -\sigma_a n_H dr \quad \text{Eq. 11}$$

where $\frac{d\phi}{dr}$ is the number of neutrons produced in one cm^3 at r, σ_a is the absorption cross section of hydrogen for neutrons, and r_1 is the thickness of the photosphere. It is assumed that, on the average, half of the neutrons are directed outward. Integration of Eq. 11 leads to

$$\Phi_n = \frac{\alpha C}{2(\alpha+\alpha')}(e^u - 1) \quad \text{Eq. 12}$$

where $\alpha = \sigma_1 a/b$, $\alpha' = \sigma_a a'/b$, $C = -\phi_o e^{\alpha+\alpha'}$ and $u = \exp-(\alpha+\alpha')e^{br_1}$.

The absorption cross section σ_a is given by:

$$\sigma_a = 7.30 \times 10^{-20} v^{-1} cm^2 \quad \text{Eq. 13}$$

where v is neutron velocity. For neutrons of 10 KeV energy, $\sigma_a \simeq 10^{-29}$ cm^2 and for protons with energy of the order of the threshold required to produce such neutrons $\sigma_1 = 5 \times 10^{-27}$ cm^2 (3). Substitution of these values in Eq. 12 leads to

$$\Phi_n \simeq 10^{-2}\phi_o \quad \text{Eq. 14}$$

which shows that for the required neutron flux $\Phi_n = 10^{11}/cm^2/sec$, it is necessary to have a flux of protons $\phi_o \simeq 10^{13}/cm^2/sec$.

The proton flux required represents an impact energy of only about 0.1% of the radiant flux of the sun.

The mechanisms analyzed above may or may not be the true mechanism of neutron production, but the authors believe that a continued study of this problem is worthwhile since the attributes of the neutron heating mechanism for the corona are so desirable.

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