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ENERGY SOURCE FOR THE SOLAR CORONA

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ABSTRACT

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.

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CHAPTER I

INTRODUCTION

In recent years investigations of the solar corona and interplanetary space have provided considerable amounts of information concerning the structure of the corona. Despite these impressive advances, no definite conclusion has yet been made concerning the source of energy which maintains the high coronal temperature. At the present time, there is no quantitative model for coronal heating. This is due to the fact that the distribution of temperature and chemical composition of the chromosphere and corona, which has an important effect on the mode of energy transfer, is not well known.

The only heating process that has been considered seriously is the dissipation of hydrodynamic and hydromagnetic waves generated by the convective motions in the ionization zone beneath the photosphere, and by the photospheric granules, and spicules in the chromosphere. The detailed objections to the above theory and other qualitative models for the heating of the corona are given in Chapter III.

In view of the difficulties with the above mentioned theories, it was suggested by R. G. Fowler and the author[1] that the heating of the corona is due to infiltration of the corona by a flux of neutrons emerging from the sun. Upon further investigation, a steady state model for the corona has been developed. A flux of protons, electrons and neutrons leaves the photosphere. The neutrons decay in the corona and release electrons and protons which collide with the coronal gas and distribute their energy. The decay energy of the neutrons is considered as the main source of the coronal energy.

Conservation laws of mass, momentum, and energy are applied to the corona and the necessary input flux is found to be $10^{11}/cm^2/sec$ at the base of corona. One possible source of the neutrons is production in the solar photosphere by returning protons which have been unable to escape the solar magnetic field. $N^{14}(p,n)O^{14}$ is considered as the most suitable reaction for the production of neutrons in the photosphere during quiet times.

CHAPTER II

THE SOLAR CORONA

Before considering the heating of the corona, it is necessary to consider the physical conditions prevailing in the coronal plasma.

Spectrum

The light of the corona is usually divided into three components:

(i) The L-Corona which refers to coronal line emission. During total solar eclipses, the L-Corona shows emission lines of highly ionized gases such as CaXII-CaXV, FeX-FeXVI, NiXII-NiXVI, etc. Table I shows typical observed lines of the corona.

(ii) The K-Corona, is the continuous spectrum of partly polarized light. The light is photospheric light which is scattered by free electrons with high kinetic temperature.

(iii) The F-Corona is a continuous spectrum with Fraunhofer lines. The F-Corona is solar radiation diffracted by interplanetary dust. The variation of the

TABLE I

THE EMISSION LINES OF THE SOLAR CORONA

λ	Relative intensity			Element and multiplet		Ionization potential (volts)	Observer	
	GROTRIAN 1929	LYOT 1934–36	RIGHINI 1936					
3328·1	1·0	—	—	Ca XII	$^2P_{3/2}$–$^2P_{1/2}$	589	LEWIS	1908
3388·10	16·4	—	17·5	Fe XIII	$^3P_2$–$^1D_2$	325	NAEGAMWALA	1898
3453·13	2·3	—	12·9	—		—	NAEGAMWALA	1898
3533·42	—	—	1·8	—		—	LEWIS	1908
3600·97	2·1	—	1·0	Ni XVI	$^2P_{1/2}$–$^2P_{3/2}$	455	LEWIS	1908
3642·87	—	—	0·9	Ni XIII	$^3P_1$–$^1D_2$	350	DYSON	1900
3800·77	—	—	1·1	—		—	FOWLER, LOCKYER	1898
3986·88	0·7	—	2·8	Fe XI	$^3P_1$–$^1D_2$	261	FOWLER	1893
3997	—	—	—	—		—	LYOT, DOLLFUS	1952
4086·29	1·0	—	—	Ca XIII	$^3P_2$–$^3P_1$	655	FOWLER	1893
4231·4	2·6	—	6·0	Ni XII	$^2P_{3/2}$–$^2P_{1/2}$	318	FOWLER	1893
4311·5	—	—	—	—		—	DYSON	1900
4351	—	—	—	—		—	LYOT, DOLLFUS	1952
4359	—	—	—	—		—	HILLS and NEWALL	1896
4412	—	—	—	—		—	DUNHAM	1937
4567	1·1	—	—	—		—	HILLS and NEWALL	1896
4586	—	—	—	—		—	FOWLER, LOCKYER	1898
5116·03	4·3	2·1	4·8	Ni XIII	$^3P_2$–$^3P_1$	350	DYSON	1905
5302·86	100	100	100	Fe XIV	$^2P_{1/2}$–$^2P_{3/2}$	355	HARKNESS	1869
5445·2	—	—	—	—		—	WALDMEIER	1950
5536	—	—	—	—		—	DYSON	1905
5694·42	—	1·3	—	—		—	LYOT	1935
6374·51	8·7	2·3	4·7	Fe X	$^2P_{3/2}$–$^2P_{1/2}$	233	CARRASCO	1914
6701·83	5·4	2·7	—	Ni XV	$^3P_0$–$^3P_1$	422	GROTRIAN	1929
7059·62	—	3·3	—	—		—	LYOT	1936
7891·94	—	2·4	—	Fe XI	$^3P_2$–$^3P_1$	261	LYOT	1935
8024·21		1·1	...	Ni XV	$^3P_1$–$^3P_2$	422	LYOT	1936
10746·80		200	—	Fe XIII	$^3P_0$–$^3P_1$	325	LYOT	1936
10797·95		125		Fe XIII	$^3P_1$–$^3P_2$	325	LYOT	1936

intensity of various components of the corona is shown in Fig. 1.

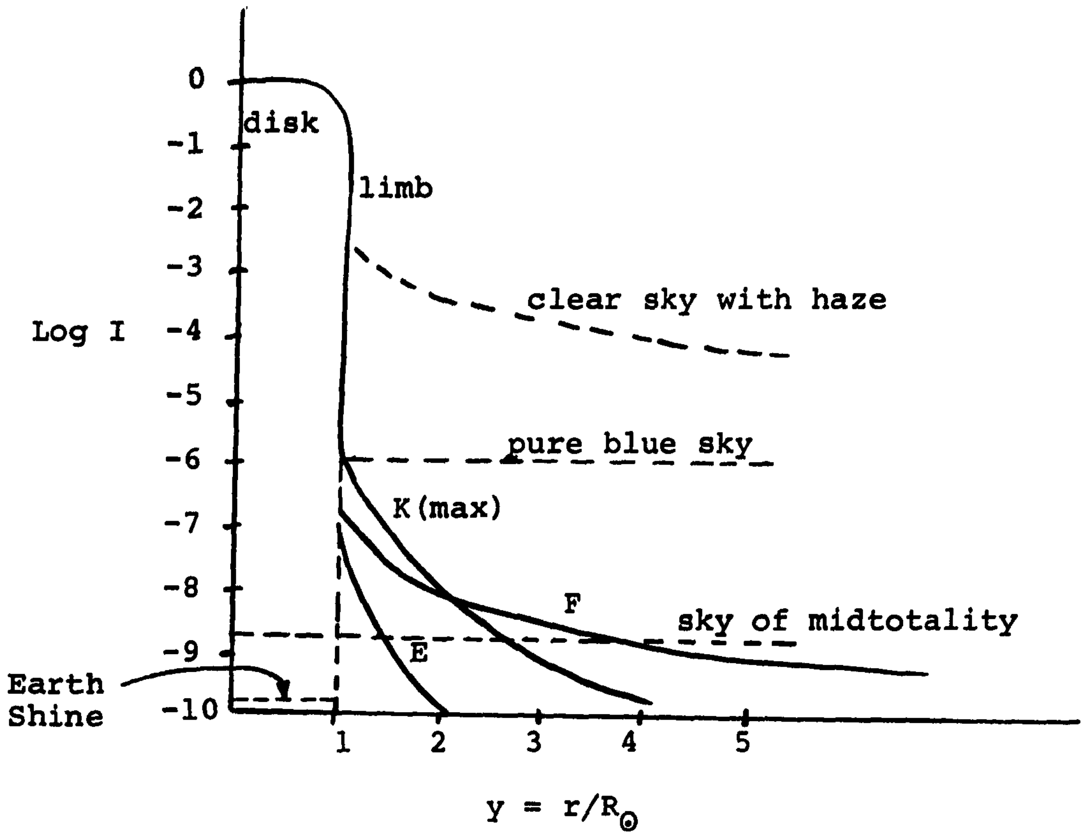

Figure 1. The Relative Intensities of the Components of Coronal Light.

Density

Several methods have been used to determine the coronal density. The most common way follows directly from measures of the intensity of the polarized light scattered by the electrons. A compilation of electron densities in the equatorial solar corona derived from different techniques[4] is shown in Fig. 2 and Table II. The result of a theoretical model by Whang, Liu and Chang is also given in Fig. 2 for comparison. Many theoretical models for density distribution have been developed. Table II is a model solar atmosphere constructed by Unsöld[5]. Baumbach[6] has derived the following formula for the electron density in the corona:

$$n_e(y) = 10^8(0.036^{-3/2} + 1.55y^{-6} + 2.99y^{-16}) \quad (1)$$

where $y = r/R_{\odot}$, $R_{\odot}$ is the radius of the sun and r is the distance from the center of the sun.

Temperature

The temperature of the corona is deduced from a variety of observations. The emission lines of the L-Corona indicate an ionizationa and excitation temperature of the order of 10^6°K. From the intensity measurement of the K-Corona an electron temperature of about 1.5×10^6°K is deduced. The measured intensity of the x-ray spectrum of the corona is thought to correspond to an electron temperature of 7.5×10^5°K. The radio emission of the corona indicate an electron temperature of order 7×10^5°K at the base of the corona.

A kinetic temperature of approximately 1.5×10^6°K has been obtained from various methods. The following

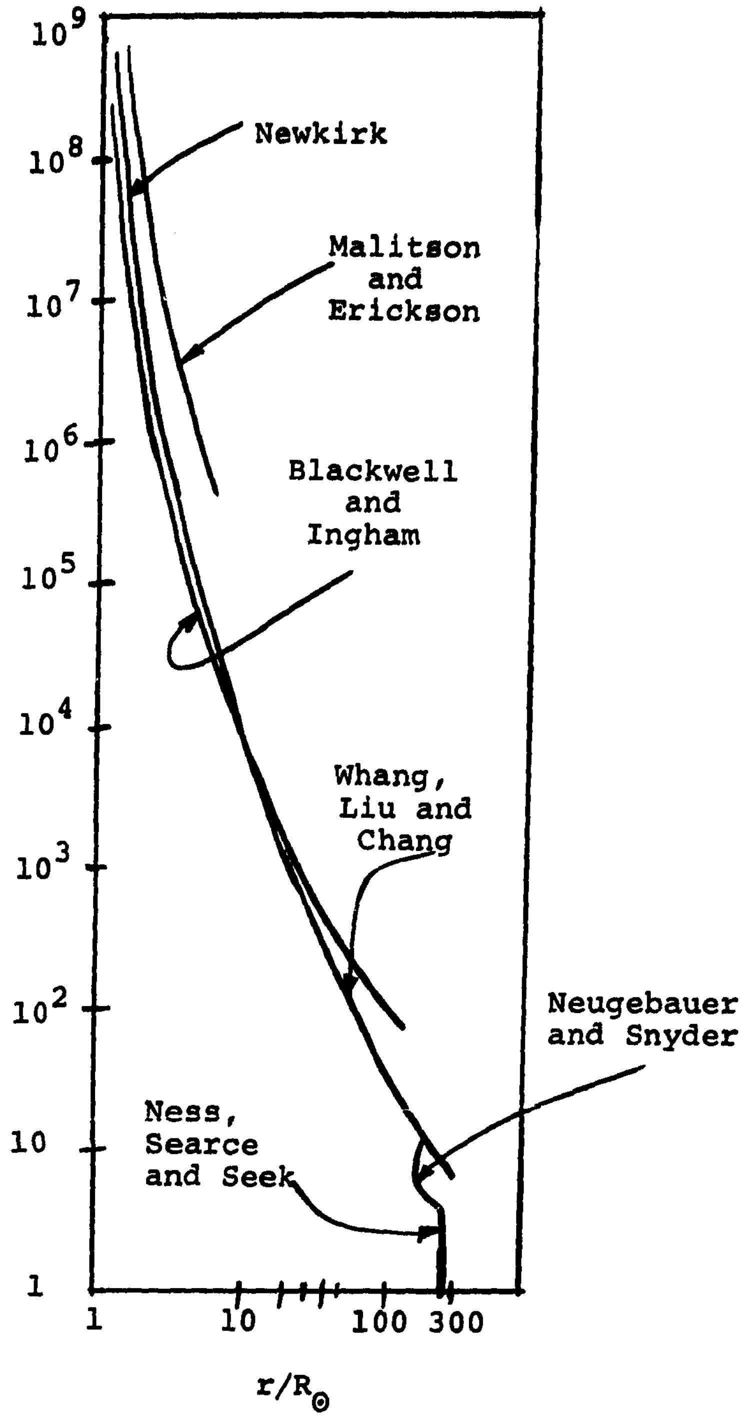

Figure 2. Coronal Electron Densities.

TABLE II

SOLAR ATMOSPHERE

Height h (km)	Solar radii	Temp. (T °K)	Gas pressure (dynes/cm²) log P_g	Electron pressure (dynes/cm²) log P_e	Electrons/cm³ log N_e	Turbulent velocity ξ_t (km/sec)	Layer	Main energy transfer
1,400,000	3.0	$2 \cdot 10^6$	−3.8	−4.1	5.5		⋮	
700,000	2.0	$2 \cdot 10^6$	−2.8	−3.1	6.4			
350,000	1.50	$2 \cdot 10^6$	−2.1	−2.4	7.2		Corona	Thermal conduction
42,000	1.06	$2 \cdot 10^6$	−0.9	−1.2	8.4			
20,000	1.03	$2 \cdot 10^6$	−0.8	−1.1	8.5		↓	
		↕ Very inhomogeneous				~15	Transition layer	Mechanical energy
3000		~4–6000	0.2	−1.7	10.5		↑	
2000	•••	~4–6000	0.5	−1.4	10.8	12	Chromosphere	Radiation
1000		~4–6000	1.2	−0.9	11.3	7		
	Opt. depth τ_{500}							
Solar limb: 0	0.005	4090	4.1	−0.5	11.7	1–2	↓ ↑	
	0.01	4295	4.3	−0.3	12.0			
	0.05	4855	4.6	+0.2	12.4			
	0.1	5030	4.8	+0.4	12.6		Photosphere	Radiation
	0.5	5805	5.1	1.2	13.3	2		
−200	1.0	6400	5.2	1.8	13.8		↓	
	2.0	7180	5.3	2.4	14.4		Hydrogen	
−280	•••	10^4	5.3	4.0	15.86	2	convection zone	Convection
	Solar radii							
−16,000	−0.02	10^5	9.4	9.1	20.0	0.3	↓	
−140,000	−0.2	10^6	12.3	12.0	21.9	0.0		Radiation

derivation from kinetic temperature is due to Alfvén[7]:

Consider the corona to be neutral and in thermal equilibrium; let n be electron density. The gas pressure is given by

$$P = 2nkT \qquad (2)$$

The gravitational force acting on a cubic centimeter is $g_s n m_H r^{-2}$ where m_H is the mass of hydrogen atom and $g_s = 2.74 \times 10^4$ cm/sec^2 is the acceleration due to gravity at the sun's surface. It is assumed that the force is equal to the pressure gradient i.e.

$$\frac{dP}{R_\odot dr} = \frac{-g_s n m_H}{r^2} \qquad (3)$$

Differentiating Eq. 2 we get

$$\frac{dP}{dr} = 2kT\,\frac{dn}{dr} + 2kn\,\frac{dT}{dr} \qquad (4)$$

From Eq. 3 and Eq. 4

$$2k\left(T\frac{dn}{dr} + n\frac{dT}{dr}\right) = \frac{-g_s R_\odot n m_H}{r^2} \qquad (5)$$

or

$$\frac{d}{dr}\left(\frac{T}{T_o}\right) + \frac{1}{n}\,\frac{dn}{dr}\,\frac{T}{T_o} = -\,\frac{1}{r^2} \qquad (6)$$

where $T_o = \frac{g_s R_{\odot} m_H}{2k} = 11.6 \times 10^6$°K. From the solution of Eq. 5

$$\frac{T}{T_o} = -\frac{1}{n}\int \frac{n}{r^2}\,dr \qquad (7)$$

using the expression for n that was given in Eq. 1 the following is obtained

$$\frac{T}{T_o} = \frac{1.23\ r^{-7} + (2.99/17)r^{-17}}{1.23\ r^{-6} + 2.99\ r^{-16}} \qquad (8)$$

upon substitution of r=1, $T \cong 10^6$°K.

Precisely similar results are obtained from the doppler width of the emission lines.

It is believed that the reason for obtaining different temperature is due to non-systematic motion of the gas in the corona (30 km/sec) and the solar wind. Table III gives the presumed speed of turbulence for the outer layers of the sun.

TABLE III

VELOCITY OF TURBULENCE FOR THE OUTER LAYERS OF THE SUN

Region	Speed in Km/Sec
Photosphere	1.8
Low Chromosphere	12.0
High Chromosphere	18.0
Corona	30.0

Abundance of Elements

Table IV gives the abundance ratio of atoms to electrons as found by Wooley and Allen[8].

TABLE IV

ATOMS PER ELECTRON IN THE CORONA

H	F_e	N_i	C_a	A
0.75	4.7×10^{-5}	1.9×10^{-6}	1.6×10^{-6}	8×10^{-8}

Table V gives the relative abundances of nuclear species by number, based on 1.0 for Oxygen [9].

The Solar Wind

The outward flow of the coronal gas is termed the solar wind. The quiet-day velocity of the solar wind near the earth is in the range 250-400 km/sec. The total flux (quiet-day) is of order 10^9 protons/cm^2/sec at the orbit of earth.

Parker[10] was the first one who pointed out that the corona is not static but expanding and developed the following model:

Consider the corona to be in a state of stationary expansion. The hydrodynamic equation for such a process is

$$V \frac{dV}{dr} + \frac{1}{NM} \frac{dP}{dr} + \frac{GM_{\odot}}{r^2} = 0 \qquad (9)$$

TABLE V

RELATIVE ABUNDANCES OF NUCLEAR SPECIES
BY NUMBER, BASED ON 1.0 FOR OXYGEN

Element	Solar Cosmic Rays	Photosphere	Corona	Galactic Cosmic Rays
$_{2}$He	107±14	?	445.0	48.0
$_{3}$Li	--	$<10^{-5}$	--	0.3
$_{4}$Be- $_{5}$B	<0.02	$<10^{-5}$	--	0.8
$_{6}$C	0.59±0.07	0.6	1.3	1.8
$_{7}$N	0.19±0.04	0.1	0.1	≲0.8
$_{8}$O	1.0	1.0	1.0	1.0
$_{9}$F	<0.03	0.001	--	≲0.1
$_{10}$Ne	0.13±0.02	?	0.11	0.3
$_{11}$Na	--	0.002	0.01	0.19
$_{12}$Mg	0.043±0.011	0.027	0.20	0.32
$_{13}$Aℓ	--	0.002	0.01	0.06
$_{14}$Si	0.033±0.011	0.035	0.22	0.12
$_{15}$P-$_{21}$Sc	0.057±0.017	0.032	--	0.13
$_{22}$Ti-$_{28}$Ni	≲0.02	0.006	~0.1	0.28

where $V(r)$ is the radial expansion velocity as a function of distance r from the center of the sun, N is the number of atoms per unit volume, G is the gravitational constant, and P is the hydrostatic pressure. Since the coronal gases are fully ionized and largely hydrogen, M is the mass of the hydrogen atoms and the hydrostatic pressure is $P = 2NkT$. Conservation of mass requires that

$$NVr^2 = N_o V_o a^2 \qquad (10)$$

where the subscript zero denotes the value at the reference level $r = a$. Parker chooses $a = 10^6$km $N_o = 10^7/\text{cm}^3$. We consider first an isothermal corona, $T = T_o \approx 2 \times 10^6\,^\circ\text{K}$ and introduce the dimensionless velocity.

$$U \equiv \frac{(1/2)\,\rho_o V^2}{P_o} \qquad (11)$$

and the dimensionless gravitational potential.

$$H \equiv \frac{GM_\odot \rho_o}{aP_o} \qquad (12)$$

We let $\zeta \equiv r/a$. Using these terms and integrating Eq. 9 we get

$$U^2 - \ln U - 2\ln\zeta - H/\zeta = U_o^2 - \ln U_o^2 - H \qquad (13)$$

where $U_o = (1/2)\,\rho_o V_o{}^2/P_o$. The solution of Eq. 13 gives a one parameter family of curves $U(\zeta)$ for any given T_o, with U_o as parameter. The general form of the family is sketched in Fig. 3.

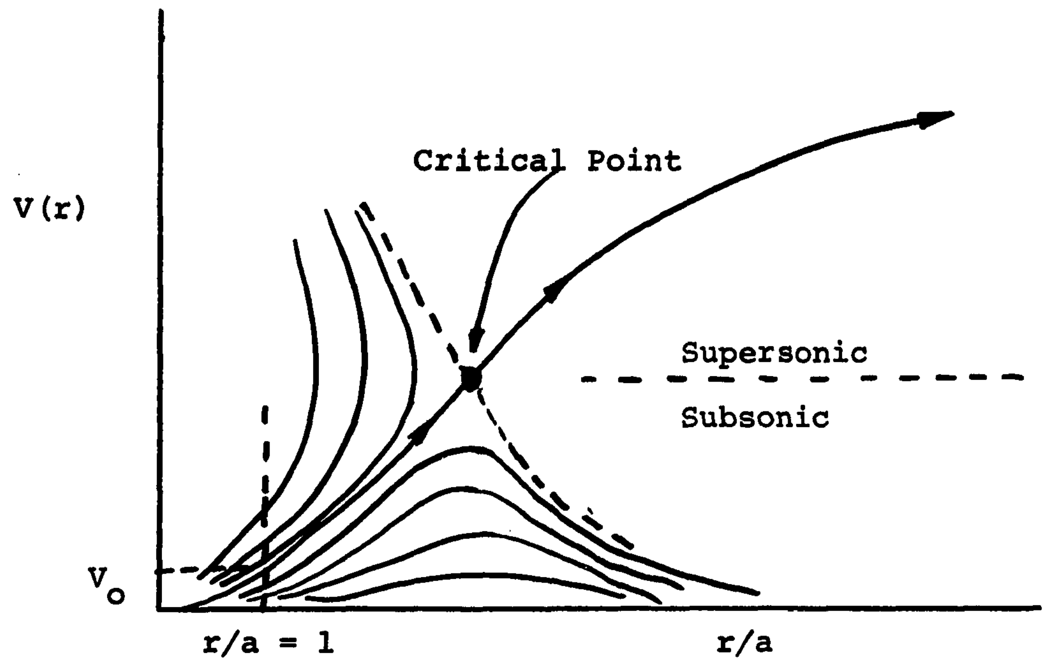

Figure 3. The Family of Solutions of Eq. 13.

The solution of physical interest is the solution starting from the origin and passing up through the critical point to supersonic velocity at infinity. The expansion velocity as a function of radial distance is shown in Fig. 4 for a number of coronal temperatures.

Many other models have been developed since 1961. The following is a viscous model of the solar wind developed by Whang, Liu, and Chang(11). Consider a steady, spherically symmetric solar wind; the three equations of conservation are:

$$\rho V r^2 = m \tag{14}$$

$$V \frac{dV}{dr} = - \frac{1}{\rho} \frac{dP}{dr} - \frac{GM_{\odot}}{r^2} + \frac{1}{\rho r^3} \frac{d}{dr} (r^3 \tau) \tag{15}$$

$$m\left(\frac{3}{2} a^2 + \frac{V^2}{2} - \frac{GM_{\odot}}{r}\right) + r^2 q - r^2 \tau V = mh_o \tag{16}$$

where a is the speed of sound ($a^2 = 5RT/3$), G is the gravitational constant of the sun, m is the mass flow per unit time per steradian, mh_o is the total energy flow per unit time per steradian, τ is the r component of the viscous

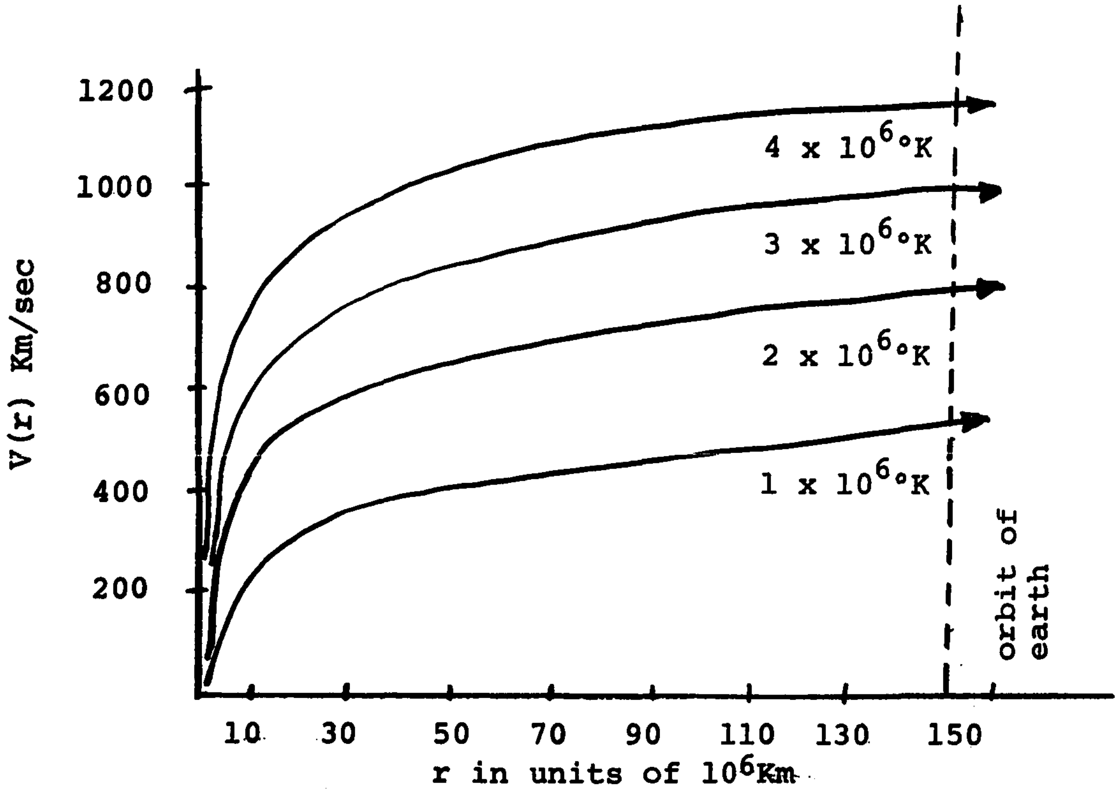

Figure 4. The Steady Expansion Velocity as a Function of Radial Distance.

stress and q is the r component of the conduction heat flux. The viscous stress and the heat flux can be expressed as

$$\tau = \frac{4}{3} \mu r \frac{d}{dr} \left(\frac{V}{r}\right) \qquad (17)$$

$$q = - k\frac{dT}{dr} = \frac{-6ka}{5R} \frac{da}{dr} \qquad (18)$$

The viscosity μ and the thermal conductivity of a fully ionized plasma are proportional to $T^{5/2}$. Upon substitution of Eq. 17 and Eq. 18 in Eq. 14, 15 and 16 and obtaining solution of Eqs. 14, 15 and 16, the electron density in Fig. 5 is found.

Magnetic Fields

The magnetic field of the sun can roughly be considered as the field of a dipole of dipole moment 10^{32}- 10^{33} gauss cm^3. In interplanetary space the lines of force of the solar field are distorted by the solar wind. The projection onto the equatorial plane of the lines of force of the solar fields extended by a quiet-day radial solar wind of 300 km/sec is shown in Fig. 6, Parker[10].

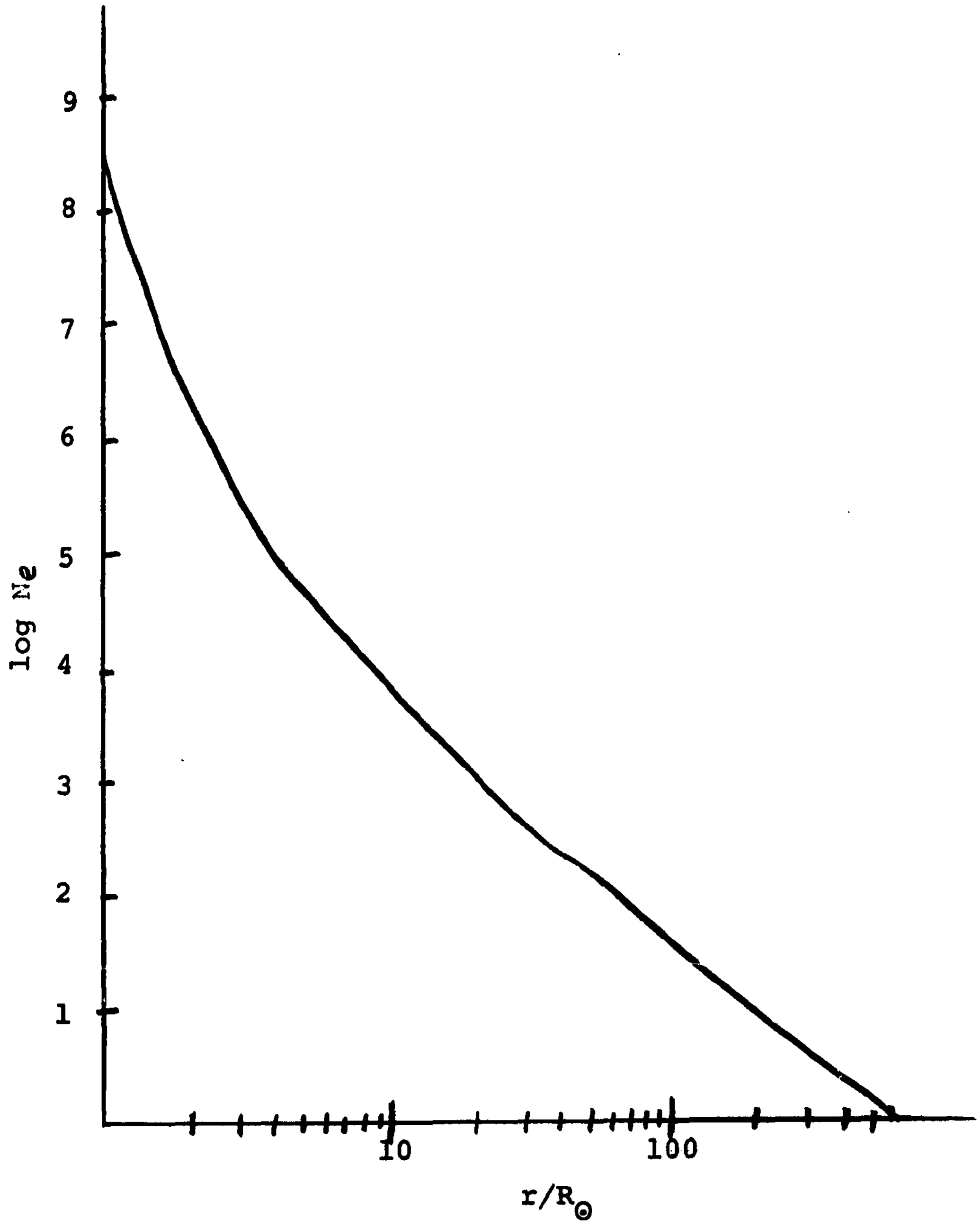

Figure 5. The Electron Density Curve.

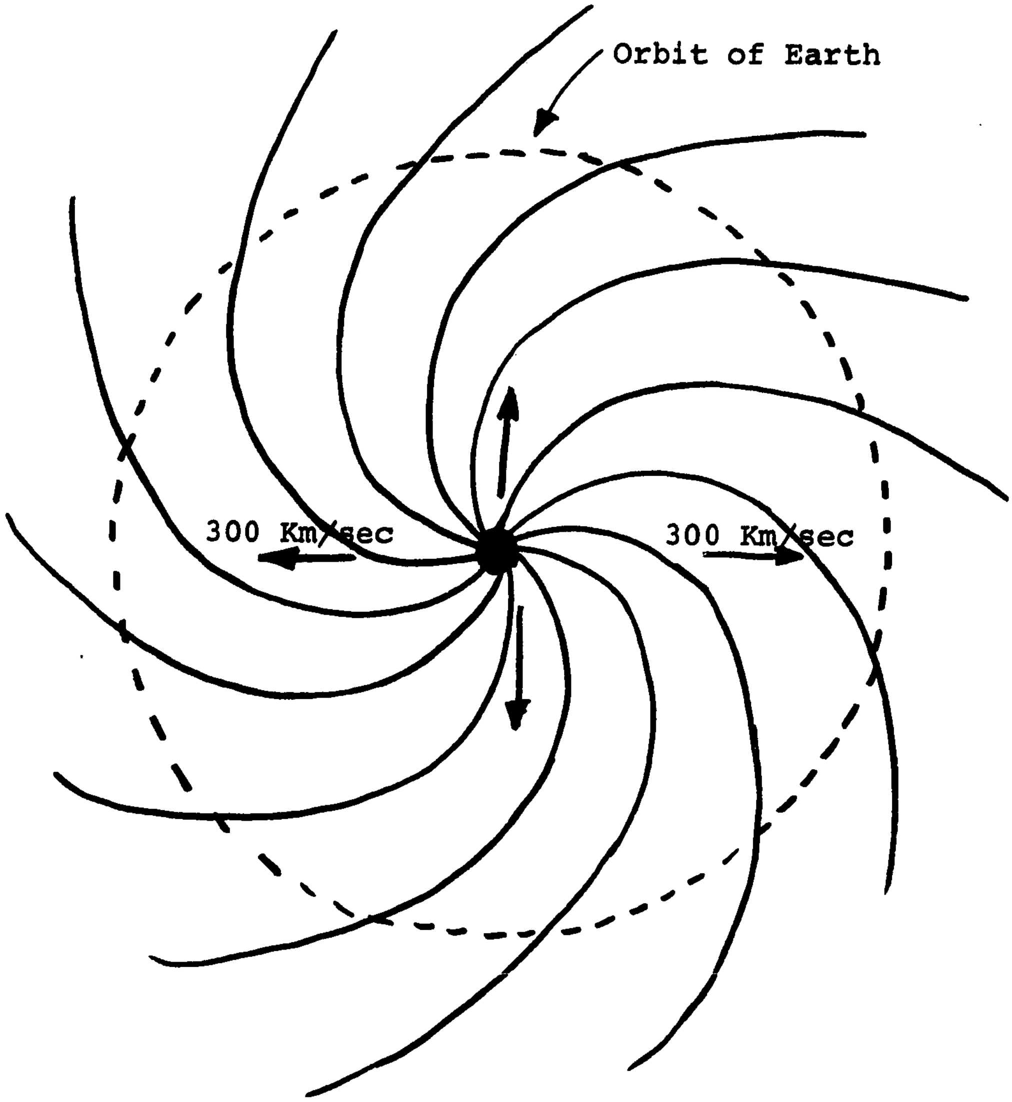

Figure 6. Magnetic Field of the Sun.

CHAPTER III

THE HEATING OF THE SOLAR CORONA

The source that supplies energy to the solar corona is believed to be either the sun itself or the interplanetary space. Early theories assumed that matter in the form of solid particles or particles of atomic dimensions fall into the corona from interplanetary space and provide the necessary energy [(12)]. These theories have been criticized in detail by Sklovskij [(13)] and others, who have shown that the flux of interplanetary particles into the corona is too small to provide the necessary energy.

The theories which assume the source of energy is the sun itself, suggest different modes of dissipation of energy into heat. Before examining these theories, it is important to evaluate the amount of heat required to maintain the corona. The corona loses heat by conduction, radiation, and convection.

In a fully ionized plasma an approximate expression for the coefficient of thermal conductivity is [(14)]:

$$K \cong 6 \times 10^{-7} T^{5/2} \text{ erg/cm}\cdot\text{sec}\cdot{}^\circ\text{K} \qquad (19)$$

From the region of high temperature in the corona heat is conducted inward to the chromosphere through the transition region and outward into interplanetary space. The total energy loss due to conduction is of order 6×10^{27} ergs/sec[10]

The radiation loss of the corona is due to the following processes:

(i) Free-free emission of hydrogen and helium.

(ii) Free-bound continuum of hydrogen and helium.

(iii) Line emission from hydrogen and helium.

(iv) Permitted line emission from heavy elements.

(v) Forbidden line emission from highly ionized heavy elements.

Orrall and Zirker [16] found the following expression for the total radiative losses

$$\epsilon_r = 1.76 \times 10^{-23} n_e^2 \text{ ergs/cm}^3 \cdot \text{sec.} \qquad (20)$$

where n_e is the electron density. The total energy loss of the corona due to radiation is of order 10^{27} ergs/sec[10]

The energy which is carried away as kinetic and gravitational potential energy by the solar wind is of order of 6×10^{27} ergs/sec.

The total energy loss of the corona is then of order 10^{28} ergs/sec. Since the corona is bound on one side by cool interstellar matter and the other side by photosphere where $T \simeq 6000°K$ it is impossible to deposit energy in the region of high temperature of the corona by conduction or radiation.

The electrical conductivity of ionized hydrogen at a temperature T is given by [14]

$$\sigma \approx 2 \times 10^7 \, T^{3/2} \text{ e.s.u.} \qquad (21)$$

in electrostatic units. The dissipation of a current density i is i^2/σ ergs/cm^3/sec. Since the electrical conductivity is very large the Joule heating is not sufficient for energy supply.

The most acceptable idea that has been put forward so far is that the corona may be heated by the dissipation of some sort of waves emitted upward from the photosphere. The waves may be sound waves, magneto-hydrodynamics waves or shock waves. The detailed discussions of these theories are given by Kuperus[15]. The main objections to these theories are:

(i) The dissipation of waves in the corona has not been observed. What have been observed so fare are long, stretched-out clouds of matter escaping from the sun with velocity of approximately 700 km/sec. Furthermore, at the orbit of earth there is a continuous flux of 10^9 protons/cm^2/sec even for the quiet sun.

(ii) Most of the wave theories have not considered the phenomenon of Landau damping of ion-acoustic waves.

In a plasma with equal ion and electron temperature, ion-acoustic waves are damped by the interaction with the ions. similarly in the chromosphere and corona the waves are more likely damped out.

CHAPTER IV

SOLAR NEUTRONS AND THE HEATING OF THE CORONA

Since 1951 the search for the solar neutrons has provided positive evidence 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 and should be considered seriously in future solar physics researches.

According to Störmer's[7] 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

$$p_{min} = \frac{ea}{cR_{\odot}} (\sqrt{3} - 2\sqrt{2}) \qquad (22)$$

where a is the magnetic moment of the sun and $R_{\odot}$ is the radius of the sun. Substituting $a \approx 10^{33}$ gauss cm^3 gives $p_{min} \approx 10^{13}$ eV/C. The large value of the momentum is inconsistent with the average particle velocity from the sun to earth (350 km/sec). A proton of energy 800 eV has velocity of 400 km/sec. This suggests that the solar particle emission must be neutral to escape.

Considerations of the above facts suggests that the 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

$$n \rightarrow P + \bar{\nu} + \bar{e} + \cdot 78 \text{ Mev} \qquad (23)$$

with a half life of about 13 minutes.

On the average the electrons carry 0.39 Mev. The electrons and protons after successive collision with the coronal gas loose their energy and so heat the corona. The average life of the neutrons 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, Fig. 7. It is assumed that the corona is electrically neutral.

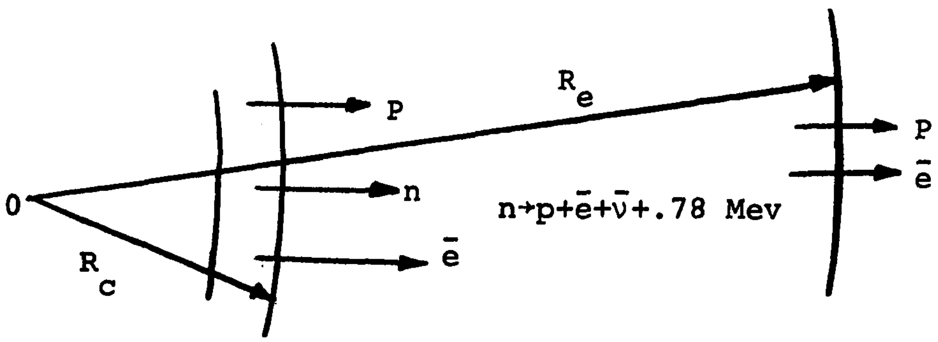

Figure 7. Neutrons and the Solar Corona.

The equations for conservation of mass, momentum and energy are

$$\Sigma_i (\nabla \cdot n_i v_i) = 0 \qquad (24)$$

$$\Sigma_i \left[n_i m_i \ (v_i \cdot \nabla) v_i + \nabla P_i - \frac{n_i m_i G M_\odot}{r^2} \right] = 0 \qquad (25)$$

$$\Sigma_i \left[\nabla \cdot n_i v_i (1/2 m_i v_i^2 + w_i - \frac{m_i G M_\odot}{r}) \right] + \nabla \cdot \frac{n_3 v_3 E_D}{2} - \varepsilon = 0 \qquad (26)$$

where

$i = 1, 2, 3$ referring to electron, proton and neutron

n_i = the density of particle i

m_i = the mass of particle i

$P_i = n_i k T_i$ = the pressure of particle i

G = the gravitational constant

$M_{\odot}$ = the mass of the sun

r = the distance in cm from the center of the sun

V_i = the velocity of particle i

$w_i = 5/2\ kT_i$

T_i = the kinetic temperature of particle i

k = Boltzman's constant

ε = the total energy lost by conduction and radiation

w_i is composed of $(3/2\ kT_i + kT_i)$ the first term represents the convection of thermal energy and the second term represents the rate at which the hydrostatic pressure of the gas crossing the position r does work on the gas ahead.

Neutrality implies

$$n_1 = n_2 \qquad (27)$$

$$en_1v_1 = en_2v_2 \qquad (28)$$

therefore

$$v_1 = v_2 \qquad (29)$$

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

$$\Sigma_i \left[1/2\ m_i n_i v_i^3 + (5/2\ kT_i) n_i v_i + \frac{n_3 v_3 E_D}{2} - \frac{n_i m_i v_i GM_\odot}{R_c}\right]$$

$$4\pi R_c^2 = \Sigma_i \left[1/2\ m_i n_i' v_i^{3\prime} + 5/2\ n_i' v_i' kT_i' - \right.$$

$$\left. \frac{n_i' m_i GM_\odot}{R_e} \right] 4\pi R_e^2 + L_R + L_c \qquad (30)$$

where R_e is the distance of earth from the center of the sun, R_c is the distance of the base of corona from the center of the sun ($R_c = 1.02\ R_\odot$) and n_i', v_i', T_i' are density, velocity, and temperature at R_e. L_R is the total energy lost by the corona in the form of radiation and L_c is total energy loss by conduction. It is assumed that all neutrons decay in the corona. From the equation of conservation of mass the following is obtained

$$(m_1 n_1 v_1 + m_2 n_2 v_2 + n_3 m_3 v_3) = \left(\frac{R_e}{R_c}\right)^2 (m_1 n_1' v_1' + m_2 n_2' v_2') \qquad (31)$$

using the approximation

$$m_2 \cong m_3 \cong m_2 + m_1$$

and the fact that $n_3m_3v_3 << n_2m_2v_2$ (otherwise more than required energy is brought to the corona). Eq. 31 is simplified to

$$m_2n_2v_2 = \left(\frac{R_e}{R_c}\right)^2 n_2m_2v_2 \qquad (32)$$

The continuous flux of proton at the orbit of earth is of order 10^9 protons/cm^2/sec substitution in Eq. 31 leads to

$$n_2v_2 \cong 10^{13} \text{ protons/cm}^2\text{/sec} \qquad (33)$$

Total energy loss due to conduction $L_c = 6 \times 10^{27}$ ergs/sec(10) and $L_R = 10^{27}$ergs/sec(10). Substitution of these values and Eq. 35 in Eq. 30 and solving for neutron flux leads to

$$n_3v_3 \cong 10^{11} \text{ neutrons/cm}^2\text{/sec} \qquad (34)$$

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

CHAPTER V

NEUTRON PRODUCTION OF THE SUN

The Observational Data

The search for solar neutrons began in 1951. Since then extensive observations with balloons, rockets and satellites have been carried out. Krishna, Apparao, Daniel, and Vijayalakshmi[18] determined a flux of 148 ± 60 neutrons/m^2/sec in the energy interval of 20-160 Mev. The experiment was carried out in a balloon flight made on a day when the sunspot number was at its peak of the 27-day variation and 6 hours after an optical flare of magnitude 3, which produced no particle intensity variations at the earth. Daniel and his group obtained a flux of $10^3/m^2$/sec in the energy interval 50-500 Mev from a balloon flight on April 15, 1966. They believe the neutrons are produced directly in the solar flares. Forrest and Chupp[20] obtained a continuous flux of $2 \times 10^{-2}/cm^2$/sec in the range 20- 120 Mev, Webler and Ormes[21]. determined a flux of $24/m^2$sec for neutrons of energy > 100 Mev during quiet time. Similar results are obtained from many other experiments. The results of important experiments are shown in Table VI.

TABLE VI

OBSERVED NEUTRON FLUX

Neutron Energy Range in Mev	Neutron Flux at Earth 1 m^2/sec	Solar Activity	Reference
20-160	148±60	Flare	(18)
50-500	1000	Flare	(19)
20-120	200	Small Flare	(20)
>100	24	Quiet Sun	(21)
1-20	100	?	(22)
10^{-2}-10	20	Quiet Sun	(23)

The Origin of Neutrons

There are two possibilities for the source of neutrons. The first possibility is that neutrons are produced in the interior of the sun and work their way to the surface. According to Weizsacker's[24] theory, the reaction chains which occur in stellar interiors leads to production of deuterons. The deuterons, which are more than 10^{-5} as abundant as hydrogen, will produce neutrons according to the following reaction:

$$D + D \rightarrow H_e^3 + n + 3.25 \text{ Mev} \qquad (35)$$

The neutrons created from this reaction on the average will carry 2.45 Mev energy.

The cross section for reaction (35) for low and high energies is well known. If n_i is the number of ions in a

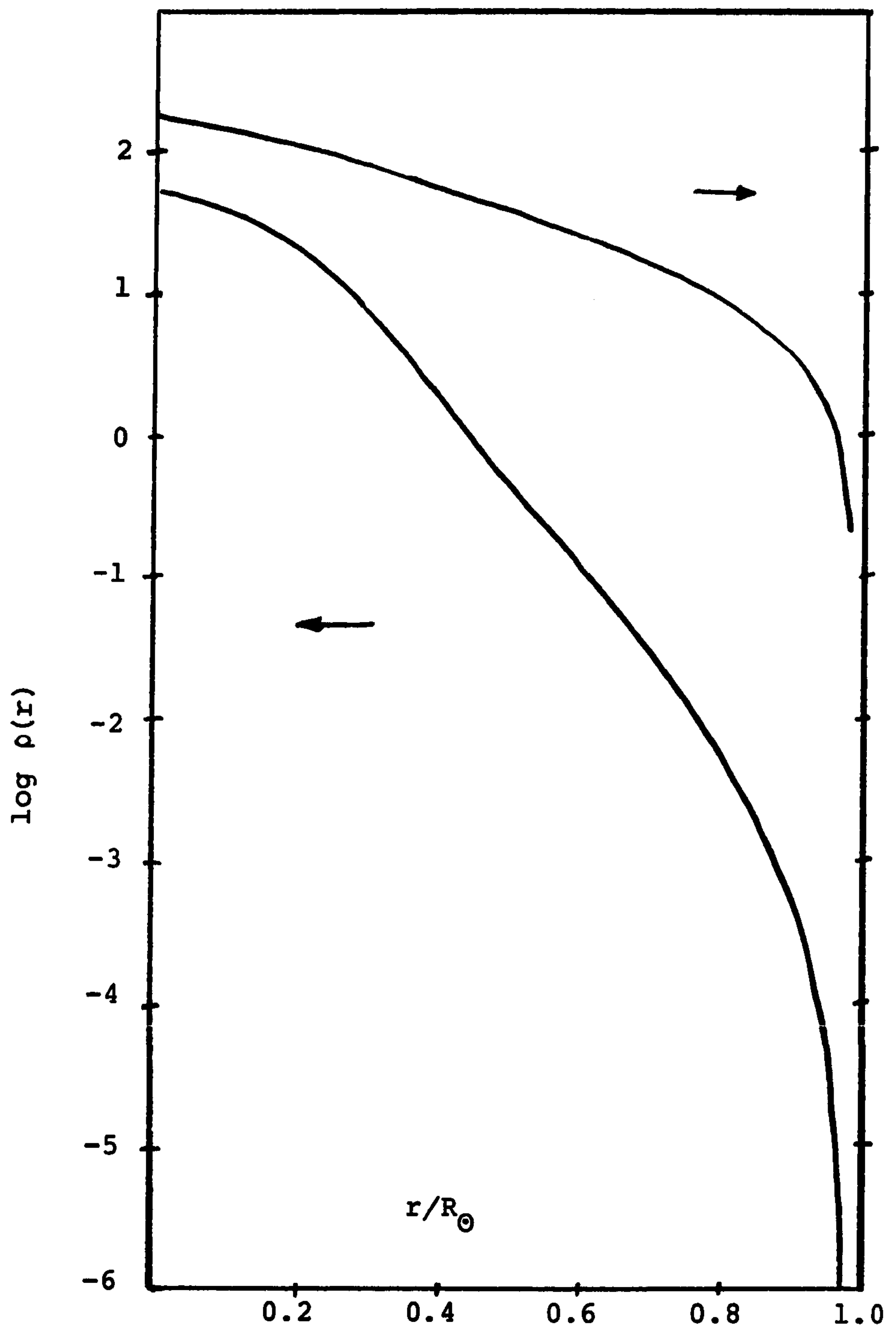

Figure 8. Temperature and Density Distribution of the Sun on the Basis of Weyman's Model (27).

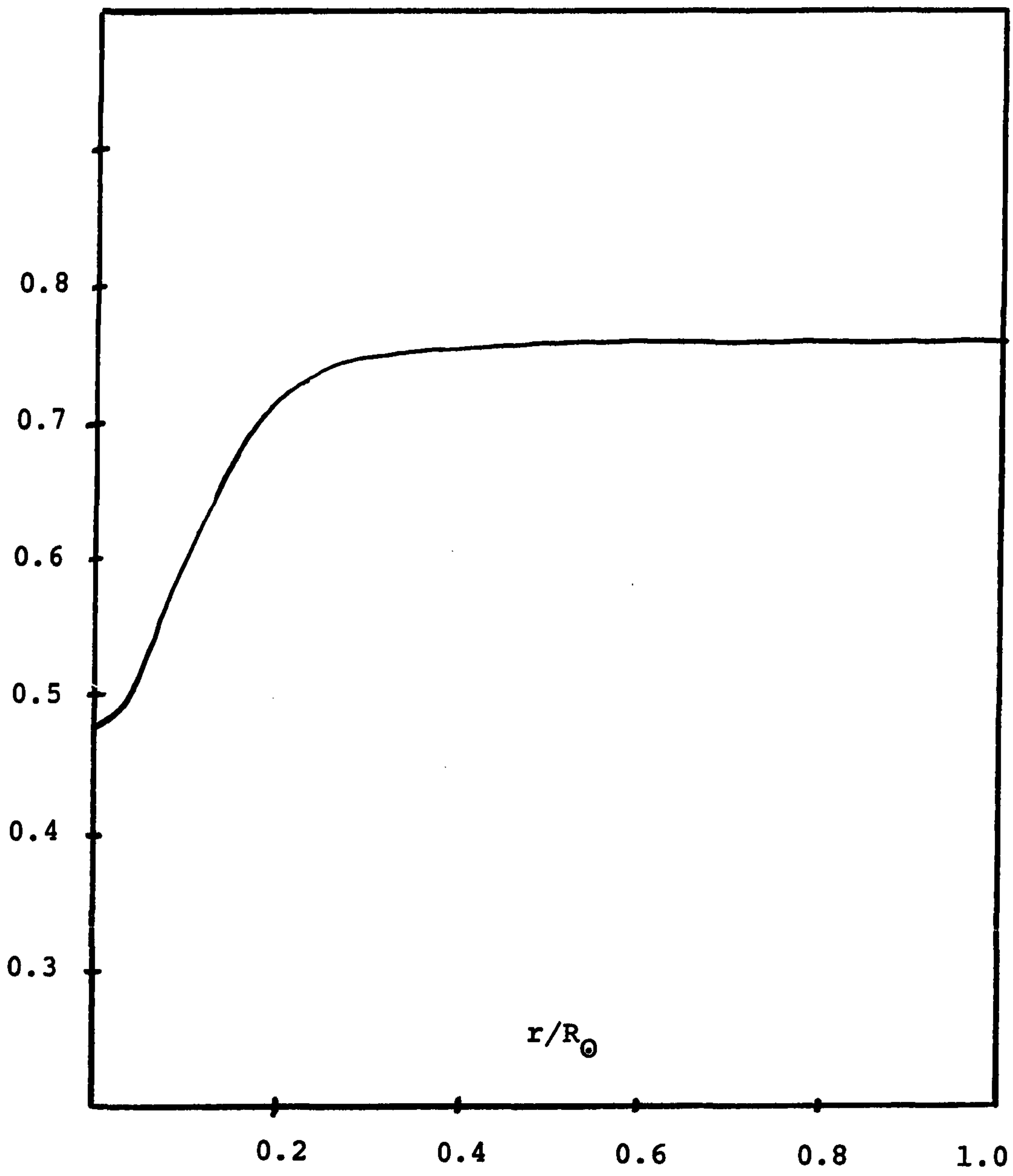

Figure 9. Mass Fraction of Hydrogen on the Basis of Weyman's Model (27).

cubic centimeter of a plasma, σ is the reaction cross section, and V is the relative velocity, then the number of reactions/cm^3/sec is given by:

$$R_{11} = \frac{1}{2} n_i^2 \langle \sigma V \rangle_{Av} \quad (36)$$

For a Maxwellian distribution with temperature T in Kev, $\langle \sigma V \rangle_{Av}$ for the DD reaction derived by Gamow[25] is:

$$\langle \sigma V_{DD} \rangle_{Av} = 2.6 \times 10^{-14} T^{-2/3} \exp\left(-18.76 T^{-1/3}\right) \quad (37)$$

The temperature and density of hydrogen inside the sun are generally assumed to be known. If following Weizsacker, the density of deuterons is taken as about 10^{-5} times the density of hydrogen, then the total neutron generation of the sun can be calculated. Kinman[26] has obtained an upper limit of $D/H < 4 \times 10^{-5}$ from the absorption spectrum of the sun. From Table VII, Fig. 9, and Eq. 37, Table VIII is obtained.

Table VIII shows at $r > .85\ R_\odot$ no neutron is produced from the DD reaction. The neutrons decay according to Eq. 23 and are captured by protons

$$n + P \rightleftarrows D + \gamma \quad (38)$$

Due to the change of concentration, the neutrons diffuse out from the production region. The flux of a particle at

TABLE VII

TEMPERATURE AND DENSITY OF THE SUN FROM MASEVICH'S MODEL[28]

$r/R_\odot$	$T \times 10^{-6}$ °K	Density in g/cm^3
1.000	0.006	0.0000
0.932	0.440	0.0001
0.795	0.800	0.0129
0.676	2.200	0.1100
0.472	5.060	1.9100
0.358	7.780	7.8400
0.295	9.770	15.7000
0.262	11.000	22.0000
0.204	13.400	36.1000
0.169	15.030	45.5000
0.148	16.110	49.9000
0.000	20.700	71.6000

TABLE VIII

NEUTRON PRODUCTION OF THE SUN

$r/R_\odot$	Temperature in Kev	R_{11}
0.000	1.300	$2 \times 10^{18.5}$
0.148	1.000	1.6×10^{18}
0.169	0.940	$10^{17.9}$
0.204	0.840	6.5×10^{164}
0.262	0.690	$2 \times 10^{15.9}$
0.295	0.610	$10^{15.2}$
0.358	0.480	$3 \times 10^{13.5}$
0.472	0.310	2×10^{11}
0.676	0.137	5×10^{5}
0.795	0.112	$5 \times 10^{3.7}$
0.850	0.080	0
0.932	0.038	0

any point due to diffusion is given by

$$j = -D\nabla n \qquad (39)$$

where j is the flux and n is concentration and D is the diffusion coefficient. For a particle which is in equilibrium in gravitational field g

$$\nabla P - nmg = 0 \qquad (40)$$

where m is the mass of the particle and g is the gravitational constant and P = nkT substitution of this value for P in Eq. 40 leads to

$$kT\nabla n - mng = 0 \qquad (41)$$

or

$$\nabla n = nmg/kT \qquad (42)$$

Substituting Eq. 42 in 39

$$j = - Dnmg/kT \qquad (43)$$

If neutrons and deuterons are in equilibrium and steady state, then

$$\frac{-D_n g n_3}{kT} - \lambda n_3 - \sigma_a N_H n_3 + \frac{1}{2} N_D^2 \langle\sigma V_{DD}\rangle_{Av} = 0 \qquad (44)$$

and

$$\frac{-D_d g N_D}{kT} + \sigma_a N_H n_3 - \frac{1}{2} N_D^2 \langle\sigma V_{DD}\rangle_{Av} = 0 \qquad (45)$$

where

D_n = diffusion coefficient of neutrons

D_d = diffusion coefficient of deuterons

N_D = density of deuterons

N_H = density of hydrogen

n_3 = density of neutrons

λ = decay constant of neutrons

σ_a = absorption cross section of neutron by hydrogen.

From the solution of Eq. 44 and Eq. 45 it was found that there is no neutron flux at the surface of the sun. Unless the temperature near the surface is higher than has been supposed, the DD reaction cannot give any contribution to the neutron flux from the sun. If at $r = .93R_\odot$ temperature is of order 2×10^6 °k instead of $.44 \times 10^6$ an adequate supply of neutrons will reach the corona.

The second possibility is the production of neutrons in the solar photosphere by returning protons which have been unable to escape the magnetic field. The detailed discussions of the neutron production in the solar photosphere are given in Chapter VI.

CHAPTER VI

NEUTRON PRODUCTION IN THE SOLAR PHOTOSPHERE

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 will be directed downward to the photosphere. The downward flux of flare accelerated protons and α particles will interact with the photosphere and produce stripping neutrons. The following neutron producing reactions can take place:

$$P + H_e^4 \rightarrow P + n + H_e^3 \qquad (46)$$

$$P + H_e^4 \rightarrow 2P + n + H^2 \qquad (47)$$

$$P + H^1 \rightarrow n + \pi^+ + H^1 \qquad (48)$$

$$P + H_e^4 \rightarrow 2P + 2n + H^1 \qquad (49)$$

$$P + C^{12} \rightarrow P + n + C^{11} \qquad (50)$$

$$P + N^{14} \rightarrow n + O^{14} \qquad (51)$$

$$P + N^{14} \rightarrow P + n + N^{13} \qquad (52)$$

$$P + N^{14} \rightarrow 2P + 2n + C^{11} \qquad (53)$$

$$P + O^{16} \rightarrow 3P + 3n + C^{11} \qquad (54)$$

$$P + O^{16} \rightarrow P + n + O^{15} \qquad (55)$$

$$P + O^{16} \rightarrow 2P + 2n + N^{13} \qquad (56)$$

$$\alpha + H^{1} \rightarrow n + P + H_{e}^{3} \qquad (57)$$

$$\alpha + H^{1} \rightarrow 2P + n + H^{2} \qquad (58)$$

$$\alpha + H^{1} \rightarrow 2P + 2n + H^{1} \qquad (59)$$

$$\alpha + H_{e}^{4} \rightarrow n + B_{e}^{7} \qquad (60)$$

$$\alpha + H_{e}^{4} \rightarrow \alpha + n + H_{e}^{3} \qquad (61)$$

$$\alpha + H_{e}^{4} \rightarrow n + P + L_{i}^{6} \qquad (62)$$

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

A rough estimate of the neutrons produced by any of the above reactions can be done as following:

Let ϕ_o be the flux of monoenergetic protons or α particles which return isotropically to the photosphere, x be the distance in cm from the base of the chromosphere towards the center of the sun. The number of neutrons produced in one second in dx at x is:

$$d\phi_n = - d\phi_x = \phi_x \sigma_{PK} N_K dx \qquad (63)$$

where σ_{PK} is the total cross section for production of neutrons, ϕ_x is the proton flux at x and N_K is the density of the particles with which protons are interacting. From Eq. 63

$$\frac{d\phi_x}{\phi_x} = \sigma_{PK} N_K dx \qquad (64)$$

or

$$\phi_x = \phi_o \exp - \int_o^x \sigma_{PK} N_K dx \qquad (65)$$

The distribution of the number of atoms (neutral or ionized) in the photosphere is shown in Table X[36]. An approximate expression for the density distribution in Table IX is:

$$N_H = ae^{bx} \qquad (66)$$

TABLE IX

DISTRIBUTION OF DENSITY AND TEMPERATURE WITH HEIGHT IN THE PHOTOSPHERE FROM A MODEL CONSTRUCTED BY ALLEN[36]

Distance from the Base of the Chromosphere	log ρ ρ=density in gm/cm³	log N N=#/cm³
x in Km		
0	-7.70	15.90
-40	-7.48	16.17
-80	-7.31	16.34
-125	-7.11	16.54
-160	-6.97	16.68
-200	-6.81	16.84
-260	-6.68	16.97
-300	-6.57	17.08
-320	-6.50	17.10
-360	-6.40	17.20
-380	-6.30	17.30
-1000	-5.80	17.80
-2000	-5.10	18.60
-5000	-4.30	19.50

where N_H is the density of hydrogen and $a = 6 \times 10^{15.3}$, $b = 8.45 \times 10^{-8}$ and x is the distance in cm.

The relative abundances of the elements in the photosphere are listed in Table X [37].

TABLE X

THE ABUNDANCES OF ELEMENTS IN THE SOLAR PHOTOSPHERE

Element	Relative Abundance
H	1
He	0.1
C	2×10^{-4}
N	3×10^{-4}
O	6×10^{-4}
Ne	3×10^{-5}
Na	2×10^{-6}
Mg	4×10^{-5}
Al	3×10^{-6}
Si	3×10^{-5}
S	1×10^{-5}
A	3×10^{-6}
Ca	4×10^{-6}
Fe	2×10^{-5}
Co	10^{-6}
Ni	2×10^{-6}

From Table XI $N_K = f_K N_H$ where f_K is the relative abundance of the K particles. Substitution of the N_K in Eq. 65 leads to:

$$\phi_x = \phi_o \exp \int_o^x \sigma_{PK} f_K \, a e^{bx} dx \tag{67}$$

but

$$\int_o^x \sigma_{PK} f_K \, a e^{bx} \, dx = \sigma_{PK} f_K \frac{a}{b} (e^{bx} - 1) \tag{68}$$

Substituting in Eq. 67

$$\phi_x = \phi_o \exp (\sigma_{PK} f_K \, a/b)(1 - e^{bx}) \tag{69}$$

or

$$\phi_n = Ce^{-\alpha e^{bx}} \tag{70}$$

where

$$\alpha \equiv \frac{\sigma_{PK} a f_K}{b} \tag{71}$$

and

$$C \equiv \phi_o e^{\alpha} \tag{72}$$

Substitution of Eq. 70 in Eq. 64 leads to:

$$\frac{d\phi_x}{dx} = -\sigma_{PK} Ce^{-\alpha e^{bx}} f_K a e^{bx} \tag{73}$$

$$= -\sigma_{PK} C \, f_K a e^{(bx - \alpha e^{bx})} \tag{74}$$

$$= -\alpha b C e^{(bx - \alpha e^{bx})} \tag{75}$$

The total neutrons which are produced in the photosphere and reach the surface of the sun is

$$\Phi_n = \frac{1}{2} \int_o^{x_1} \left(\frac{d\phi_x}{dx}\right) e^{-\int_o^x \sigma_a N_H dx} \qquad (76)$$

where σ_a is the absorption cross section of neutron by hydrogen and x_1 is the thickness of the photosphere. It is assumed that on the average half of the neutrons escape outward. Substitution of Eq. 75 in Eq. 76 leads to:

$$\Phi_n = \frac{1}{2} \int_o^{x_1} - \alpha bCe^{(bx - \alpha e^{bx})} e^{-\int_o^x \sigma_a N_H dx} \qquad (77)$$

$$\int_o^x \sigma_a N_H dx = \int_o^x \sigma_a ae^{bx} dx = \frac{\sigma_a}{b} (e^{bx} - 1)\ a \qquad (78)$$

Substituting Eq. 78 in Eq. 77

$$\Phi_n = \frac{1}{2} \int_o^{x_1} -\alpha bCe^{(bx - \alpha e^{bx})} e^{\frac{a\sigma_a}{b}(1-e^{bx})} dx \qquad (79)$$

or

$$\Phi_n = \frac{1}{2} \int_o^{x_1} -\alpha bCe^{bx - \alpha e^{bx} + \alpha'(1-e^{bx})} dx \qquad (80)$$

where

$$\alpha' \equiv \frac{\sigma_a a}{b} \qquad (81)$$

or

$$\Phi_n = \frac{1}{2}\int_0^{x_1} -\alpha b C' e^{(bx - \alpha e^{bx} - \alpha' e^{bx})} dx \qquad (82)$$

where

$$C' \equiv Ce^{\alpha'} \qquad (83)$$

or

$$\Phi_n = D\int_0^{x_1} e^{[bx - (\alpha + \alpha')e^{bx}]} dx \qquad (84)$$

where

$$D \equiv -\frac{1}{2}\alpha b C' \qquad (85)$$

To integrate Eq. 84 let

$$e^{-(\alpha+\alpha')e^{bx}} = e^u \qquad (86)$$

then

$$du = -b(\alpha+\alpha')e^{bx}dx \qquad (87)$$

and

$$e^{[bx-(\alpha+\alpha')e^{bx}]} = e^{(u+bx)} \qquad (88)$$

or

$$[\exp(u+bx)]dx = e^u du \left(\frac{1}{-b(\alpha+\alpha')}\right) \qquad (89)$$

Substitution of Eq. 89 in Eq. 84 and integration leads to:

$$\Phi_n = \frac{-D}{b(\alpha+\alpha')}\int_0^u e^u du \qquad (90)$$

or

$$\phi_n = \frac{-D(e^{u_1}-1)}{b(\alpha+\alpha')} \qquad (91)$$

where

$$u_1 = -(\alpha+\alpha')e^{bx_1} \qquad (92)$$

x_1 is the thickness of photosphere.

Eq. 91 gives the total flux of neutrons which reach the surface of the sun. The neutrons are produced by an inward flux ϕ_o of monoenergetic protons interacting with the K's particle in the photosphere.

The bombardment of the photosphere by fast protons will also produce deuteron, tritons, helium, pions, positrons and gamma rays. To suggest a specific reaction for production of neutrons, all possible reactions should be considered and examined. The reactions which produce products that are not observed should be rejected.

Consider a flux of monoenergetic protons each with E_p=100 Mev which return isotropically to the photosphere. Eq. 91 can be used for calculation of neutron flux due to different reactions. The cross section for interaction of proton with helium is shown in Fig. 10.

Consider the reactions listed in Table XI. The energy range of the neutrons produced from reactions in Table XI is given by[30]

$$0 < E_n < E_p - Q \qquad (93)$$

where E_p and E_n are the incident proton and secondary

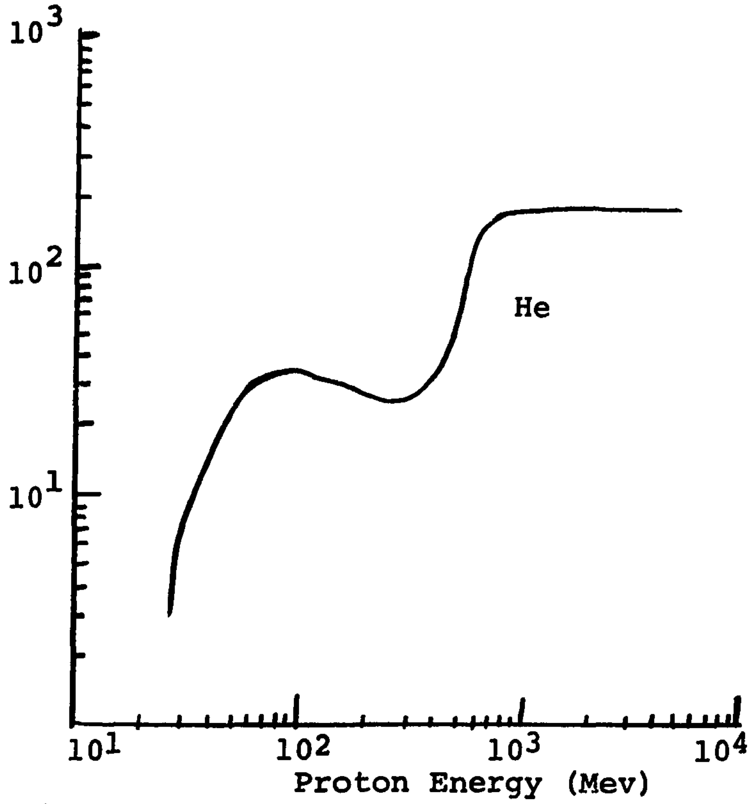

Figure 10. Cross Section for Production of Neutron in Proton Reaction with Helium.

TABLE XI

Q VALUES FOR NEUTRON PRODUCING REACTIONS[30]

Reaction	Threshold in Mev	Q in Mev
$He^4(p,pn)He^3$	25.7	20.55
$He^4(p,2p,n)H^2$	32.6	25.97
$He^4(p,2p,2n)H^1$	35.4	28.92

neutron energies, respectively. For $E_p = 100$ Mev the average value of E_n is of order 38 Mev. The cross section for absorption of neutrons by hydrogen is

$$\sigma_a = 7.30 \times 10^{-20} v^{-1} cm^2 \qquad (94)$$

where v is the neutron velocity, for 38 Mev neutron

$$\sigma_a \cong 8.5 \times 10^{-30} \ cm^2$$

The cross section for production of neutrons from interaction of 100 Mev proton with helium is 3.5×10^{-26} cm^2. The neutrons which are produced from the interaction of protons with H, C, N, O, Ne are negligible compared to the ones produced by He(29). Substitution of the values for σ_a and σ_{PK} in Eq. 91 leads to

$$\Phi_n \cong 5 \times 10^{-3} \ \phi_o \qquad (95)$$

which shows that to produce a flux of $10^{11}/cm^2/sec$ neutrons, it is required to have an inward flux of order 2×10^{13} protons/cm^2/sec to the photosphere.

In order to investigate whether the above interaction takes place in the photosphere during a flare or quiet time, it is necessary to calculate the total flux of γ rays which is produced by the incoming protons to the photosphere and compare it with observations.

Most of the γ rays are produced from the de-excitation of excited nuclei. The γ rays produced by other processes are negligible compared to the one produced from the de-excitation of nuclei. The cross sections for production of γ rays from the de-excitation of C^{12} and O^{16} are shown in Fig. 11.

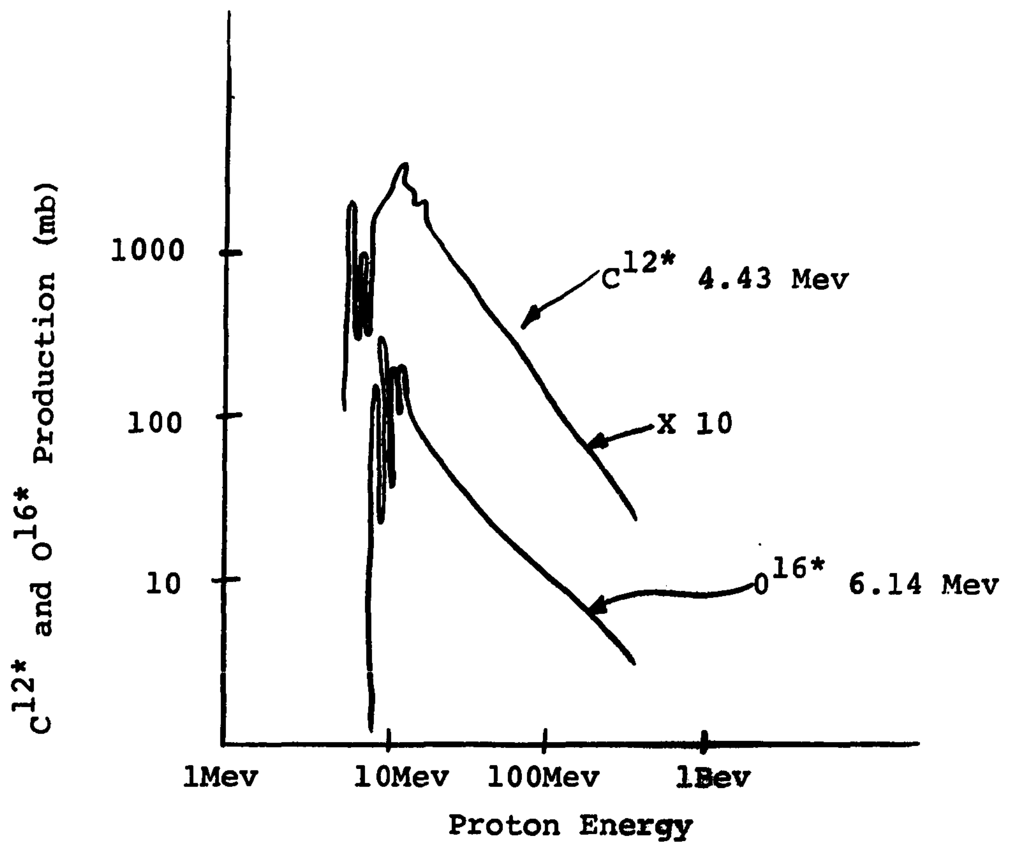

Figure 11. Excited C^{12} and O^{16} Production Cross Sections.

An estimate of the flux of γ rays which is produced from the de-excitation of nuclei can be done as following:

The number of γ rays produced in one second in dx at x is

$$d\phi'_x = -\phi'_x \sigma_{\gamma K} N_K dx \qquad (96)$$

where $\sigma_{\gamma K}$ is the cross section for production of γ rays from the de-excitation of the nuclei of density N_K and ϕ'_x is the proton flux at x. Integration of Eq. 96 leads to

$$\phi'_x = \phi_o \exp(\sigma_{\gamma K} f_K\, a/b)(1 - e^{bx}) \qquad (97)$$

where ϕ_o, f_K, a and b were defined before.

The total flux of γ rays which is produced in the photosphere and reach the surface of the sun is

$$\Phi_\gamma = \frac{1}{2} \int_o^{x_1} \frac{d\phi'}{dx}\, e^{-\int_o^x \sigma_{a\gamma} N_H dx} \qquad (98)$$

where $\sigma_{a\gamma}$ is the total absorption cross section of γ rays. The predominant types of interactions of γ rays with matter are photoelectric effect, the Compton effect, and electron-positron pair production. The total cross section is given by

$$\sigma_{a\gamma} = \sigma_{ph} + \sigma_c + \sigma_{pr} \qquad (99)$$

where σ_{ph} is the cross section for photoelectric effect,

σ_c for the Compton effect, and σ_{pr} for pair production. The linear absorption coefficient μ_ℓ is defined by

$$\mu_\ell = a_{a\gamma} n \tag{100}$$

where n is the density of the absorbing materials. The mass absorption coefficient μ_m is defined by

$$\mu_m = (\mu_\ell)/\rho \tag{101}$$

where ρ is the density in gm/cm^3 of the absorbing materials. Substitution of Eq. 101 in Eq. 98 leads to

$$\Phi_\gamma = \frac{1}{2} \int_0^{x_1} \frac{d\phi'}{dx} e^{-\int_0^x \mu_\ell dx} \tag{102}$$

It is assumed that on the average half of the neutrons escape outward. Since

$$\rho = a' e^{bx} \text{gm/cm}^3 \tag{103}$$

where $a' = 10^{-7.7}$

then

$$\int_0^x \mu_\ell dx = \int_0^x \mu_m \rho \, dx = \frac{\mu_m a'}{b} (e^{bx} - 1) \tag{104}$$

Substituting Eq. 104 in Eq. 102

$$\Phi_\gamma = \frac{1}{2} \int_0^{x_1} \frac{d\phi'}{dx} \exp\left[\frac{a'\mu_m}{b} (1 - e^{bx})\right] \tag{105}$$

but

$$\frac{d\phi'}{dx} = -\phi_o \ [\exp(\sigma_{\gamma K} f_K a/b)(1-e^{bx})]\sigma_{\gamma K} N_K dx$$

(106)

or

$$\frac{d\phi'}{dx} = -\alpha_\gamma b C_\gamma e^{(bx - \alpha_\gamma e^{bx})} \quad (107)$$

where

$$\alpha_\gamma \equiv \frac{\sigma_{\gamma K}\, a f_K}{b} \quad (108)$$

and

$$C_\gamma \equiv \phi_o e^{\alpha_\gamma} \quad (109)$$

Substitution of Eq. 107 in Eq. 105 leads to

$$\Phi_\gamma = \frac{1}{2}\int_o^{x_1} -\alpha_\gamma b C_\gamma e^{bx-\alpha_\gamma e^{bx}} e^{(\frac{\mu_m a'}{b})(1-e^{bx})} dx \quad (110)$$

or

$$\Phi_\gamma = \frac{1}{2}\int_o^{x_1} -\alpha_\gamma b C'_\gamma \ e^{[bx-\alpha_\gamma e^{bx} - \alpha'_\gamma e^{bx}]} dx \quad (111)$$

where

$$C'_\gamma \equiv C_\gamma e^{\alpha'_\gamma} \quad (112)$$

and

$$\alpha'_\gamma \equiv \frac{\mu_m a'}{b} \quad (113)$$

From Eq. 111

$$\Phi_\gamma = D_\gamma \int_o^{x_1} \exp[bx-(\alpha_\gamma+\alpha'_\gamma)e^{bx}] \quad (114)$$

where

$$D_\gamma \equiv -\frac{1}{2}\alpha_\gamma bC'_\gamma \qquad (115)$$

Integration of Eq. 114 by parts leads to

$$\Phi_\gamma = \frac{-D_\gamma(e^{u_1}-1)}{b(\alpha_\gamma + \alpha'_\gamma)} \qquad (116)$$

where

$$u_1 \equiv -(\alpha_\gamma + \alpha'_\gamma)e^{bx_1} \qquad (117)$$

Eq. 116 gives the total flux of the γ rays which escape from the sun. The cross section for the excitation of 4.43 Mev level in C^{12} by 100 Mev protons is of order $10^{-26}cm^2$ (Fig. 11). The mass absorption coefficient for 4.43 Mev γ ray is $\cong$ .053 cm^2/gm. Substitution of these values in Eq. 116 leads to

$$\Phi_\gamma \cong 10^8 \ /cm^2/sec \qquad (118)$$

The flux of 4.43 Mev γ rays which leaves the sun will produce a flux of order $10^4/cm^2/sec$ at the earth. The observed fluxes of γ rays from the sun are shown in Table XII.

Comparison of the calculated flux of 4.43 Mev γ rays with the observed flux shows that bombardment of the photosphere with a flux of 2×10^{13} protons/cm^2/sec and E_p = 100 Mev cannot occur during quiet times.

TABLE XII

OBSERVED γ RAY FLUX[31]

γ Ray Energy Range in Kev	Solar Flux Upper Limit Counts/cm^2Kev Sec
17.5- 37.5	8.1×10^{-4}
37.5- 6.0	2.7×10^{-4}
60.0- 80.0	1.5×10^{-4}
80.0-135.0	0.9×10^{-4}
135.0-185.0	0.6×10^{-4}
Mev	
1.0- 1.5	4.0×10^{-6}
1.5- 2.0	3.2×10^{-6}
2.0- 3.0	1.6×10^{-6}
3.0- 4.0	1.6×10^{-6}
4.6- 6.0	0.8×10^{-6}
6.0- 8.0	0.6×10^{-6}
8.0- 11.0	0.6×10^{-6}

A neutron which is produced in the photosphere will decay in the corona if its kinetic energy is of order 0.4 Mev. Of all possible proton initiated reactions for production of neutron, $N^{14}(p,n)O^{14}$ has the lowest threshold. Kuan and Risser[32] measured the total cross section for $N^{14}(p,n)O^{14}$ from threshold to 12 Mev. The threshold was determined to be 6.345 ± 0.015 Mev.

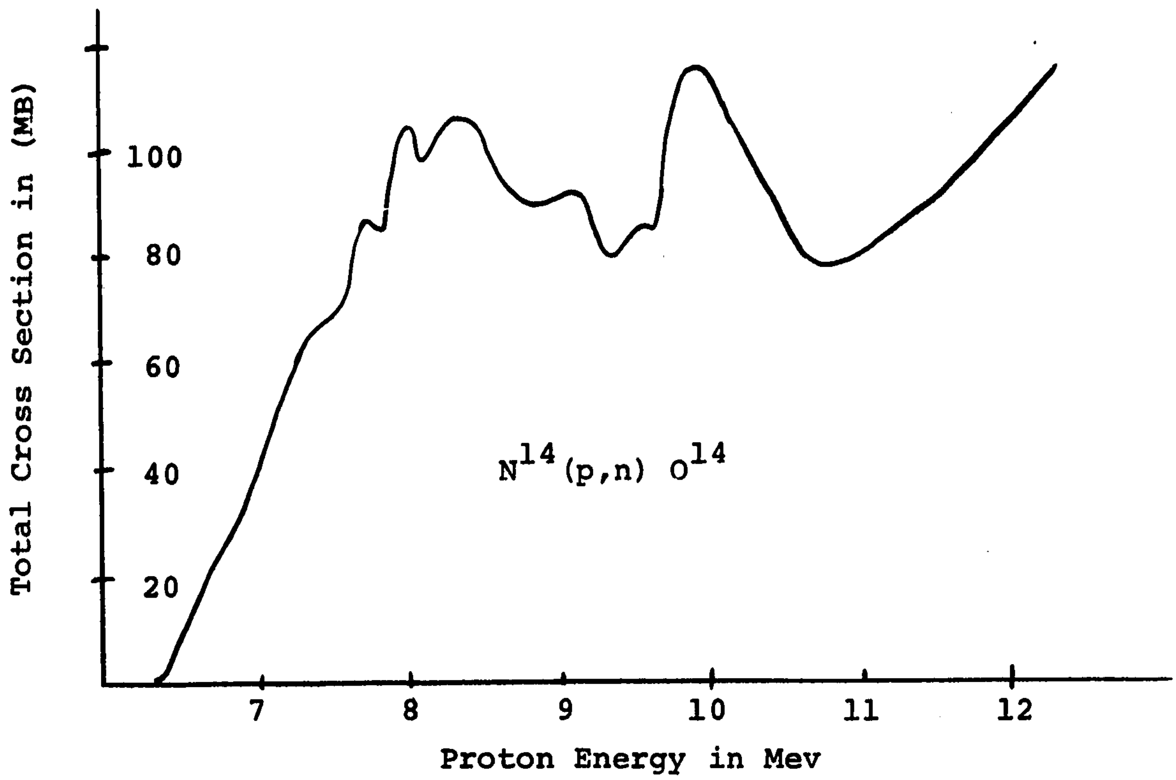

Figure 12. Total Cross Section for $N^{14}(p,n)\ O^{14}$ reaction.

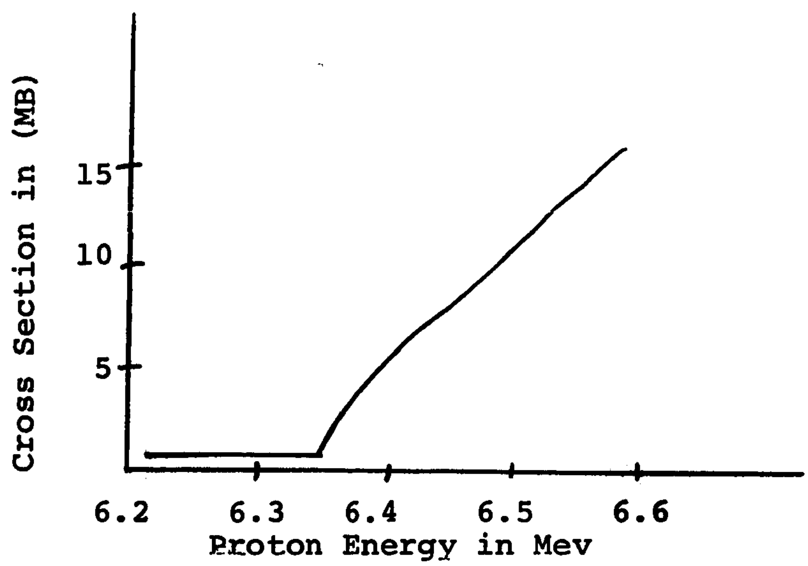

Figure 13. Total Cross Section for $N^{14}(p,n)\ O^{14}$ Near Threshold.

In order to get an estimate of the energy of the neutrons from reaction $N^{14}(p,n)O^{14}$ we can use the following relation[33]

$$Q = E_3\left(1+ \frac{M_3}{M_4}\right) - E_1\left(1- \frac{M_1}{M_4}\right) - \frac{2\sqrt{M_1E_1M_3E_3}}{M_4} \cos\phi \tag{119}$$

M_1 = mass of the proton

M_2 = mass of N^{14}

M_3 = mass of neutron

M_4 = mass of O^{14}

E_1 = proton energy

E_3 = neutron energy

$Q = -6.03 \pm 0.2$ Mev[32]

θ = the angle with forward direction

At the threshold, the neutron energy is given by

$$E_3 = E_1' \frac{M_1M_2}{(M_3+M_4)^2} \tag{120}$$

where E_1' is the threshold of the reaction. Substitution of the values for E_1', M_1, M_3, M_4 in Eq. 120 leads to

$$E_3 \cong 0.4 \text{ Mev} \tag{121}$$

Which is the energy required for neutrons to decay into the corona. Bombardment of the photosphere with proton of energy of order 6.3 Mev will not produce excited states in C^{12} and O^{16} (Fig. 11). The $N^{14}(p,n)O^{14}$ reaction is then a suitable reaction for production of neutrons during quiet times. Similarly, the reaction $C^{12}(H_e^3,n)O^{14}$ with threshold of order 1.445 ± 0.010 Mev is a suitable reaction for quiet times. The cross section for $C^{12}(H_e^3,n)O^{14}$ from threshold to 3.5 Mev was also measured by Kun and Risser[32].

For an estimate of the neutrons produced by $C^{12}(H_e^3,n)O^{14}$ or $N^{14}(p,n)O^{14}$ Eq. 91 can be used. For neutrons of 0.4 Mev energy

$$\sigma_a \cong 2.6 \times 10^{-28.5} \text{ cm}^2 \qquad (122)$$

σ_{PK} for $E_p \cong E_1'$ in reaction $N^{14}(p,n)O^{14}$ is

$$\sigma_{PK} \cong 5 \times 10^{-27} \text{ cm}^2 \qquad (123)$$

Substitution of these values in Eq. 91 leads to

$$\phi_n \simeq 10^{-3.5} \phi_o \qquad (124)$$

which shows for the required neutron flux of $10^{11}/\text{cm}^2/\text{sec}$ it is necessary to have a flux of protons $\phi_o = 10^{14.5}/\text{cm}^2/\text{sec}$.

The proton flux required represents an impact energy of only about one per cent of the radiant flux of the sun.

For the reaction $C^{12}(H_e^3,n)O^{14}$ energy of neutron near the threshold is

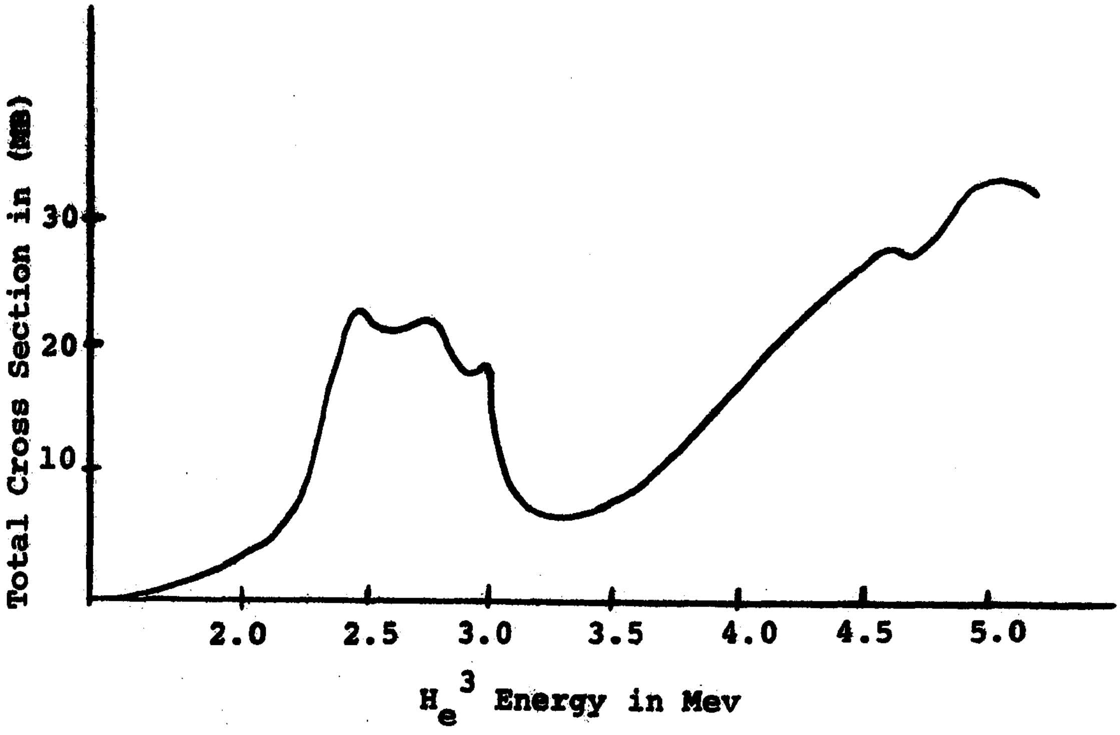

Figure 15. Total Cross Section for $C^{12}(H_e^3, n)O^{14}$ reaction.

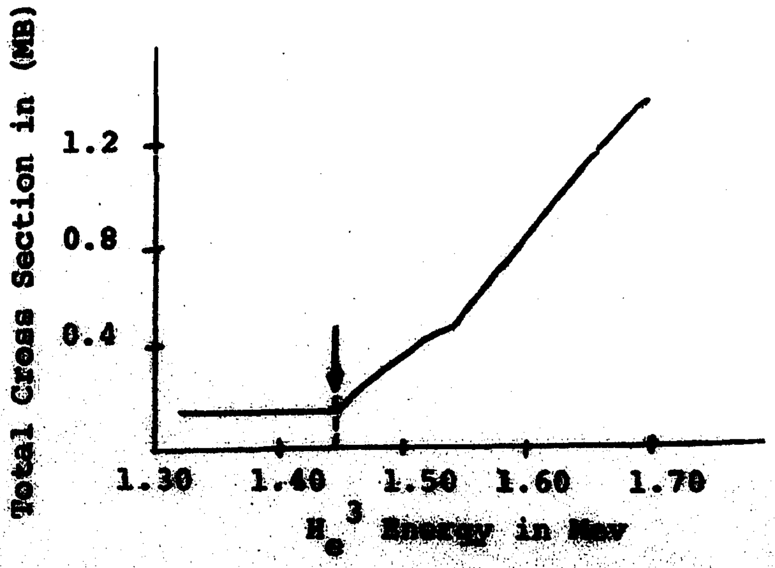

Figure 14. Total Cross Section for $C^{12}(H_e^3, n)O^{14}$ Near Threshold.

$$E_3 \cong 1.5 \times 10^{-2} \text{ Mev} \tag{125}$$

and

$$\sigma_a \cong 2.6 \times 10^{-28} \text{ cm}^2 \tag{126}$$

For $E_p \cong E_1'$

$$\sigma_{PK} \cong 0.3 \times 10^{-27} \text{ cm}^2 \tag{127}$$

Substitution of these values in Eq. 91 leads to

$$\phi_n \cong 10^{-6} \phi_o' \tag{128}$$

where ϕ_o' is the inward flux of H_e^3 and ϕ_n' is the neutron flux produced in the photosphere by H_e^3. According to Greenstein[34] the relative abundances of H_e^3 to H_e^4 is given by

$$\frac{H_e{}^3}{H_e{}^4} < 2 \times 10^{-2} \tag{129}$$

which implies that $\phi_o' \cong 10^{-3}\phi_o$. This shows that the neutron flux produced by $C^{12}(H_e^3,n)O^{14}$ is negligible compared to the one by $N^{14}(p,n)O^{14}$.

CHAPTER VII

CONCLUSION

It has been proposed that the corona is heated by neutrons originating in the photospheric layer of the sun. The neutrons which are produced from DD reaction in the solar upper interior (on the current model of the solar interior) are absorbed before reaching the surface of the sun. The neutrons produced from interaction of intergalactic cosmic rays with the solar photosphere are not enough for the heating of the corona.

Recently Schatzman[35] has shown that thermonuclear reactions which take place in the interior of stars will cause the central matter to be moved to the surface by turbulent transport or convective motions. According to this theory it is possible that matter containing neutrons might be brought to the surface of the sun.

The theory for the heating of the corona which has been presented in this dissertation is free from the criticisms which are applicable to the available theories. The assumption that the incoming particles from the sun are initially neutrons can explain the apparent propagation of charged particles across the magnetic field of the sun and the cause of the aurorae and magnetic storms. It has been shown that a charged particle cannot leave the sun in the region of the equator unless it has a momentum of order of 10^{13} ev/c. Most of the particles are ejected from the active regions near the equator with velocity of order 400 km/sec. This shows that neutral particles are initially emitted from the sun and acquire their charges in interplanetary space. Aurorae observations have shown that the flux of electrons is nearly equal to the flux of protons, a fact that could only be explained by the assumption that the ejected particles from the sun are initially neutral.

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