The Coronal Heating Process

In memory of the victims of the 11th Sept.
in United States of America

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May 2002

ABSTRACT

The aim of this study is to present the mechanism leading to the observed distribution of temperature in the Sun's corona. The mechanism described below is based only on the basic laws of mechanics, thermodynamics and experimentally or observationally confirmed facts.

On the base of the basic laws of thermodynamics we must draw a conclusion that the free way between the collisions for the particles of the solar gas is the longest towards the decreasing pressure, i.e. towards the space vacuum. The most probable direction of movement for the particles is therefore the direction "from the Sun towards the space vacuum". This anisotropy of thermal movements causes that the fastest i.e. the hottest particles of the solar gas run away from the Sun the fastest (with the biggest velocity). The initial increase of the chromosphere's temperature is caused by the escape of the fastest electrons. Because of the smaller radius they have much bigger free way between the collisions, what allows them to transfer their kinetic energy to the higher layers of the chromosphere. Similar escape of the hottest atoms and ions in the transitional layer causes acceleration of the increase of the temperature in the gas of the Sun corona.

The rapid temperature's increase of the Sun's atmosphere's gas is therefore the effect of the escape of the fastest (the hottest) particles towards the decreasing pressure, i.e. towards the space vacuum.

INTRODUCTION

One of the "Big Questions" of the solar physics, which are listed on the NASA's website (http://science.nasa.gov/ssl/PAD/SOLAR/quests.htm) is the unsolved heating mechanism of the Sun corona. Quotation (NASA's web site):

"The Sun's outer atmosphere (the Corona) is hotter than 1,000,000°C while the visible surface has a temperature of only about 6000°C. The nature of the processes that heat the corona, maintain it at these high temperatures, and accelerate the solar wind is a third great solar mystery. Usually temperatures fall as you move away from a heat source. This is true in the Sun's interior right up to the visible surface. Then, over a relatively small distance, the temperature suddenly rises to extremely high values. Several mechanisms have been suggested as the source of this heating but there is no consensus on which one, or combination, is actually responsible." End of quotation.

The aim of this study is to present the mechanism leading to the observed distribution of temperature in the Sun's corona. The mechanism described below is based only on the basic laws of mechanics, thermodynamics and experimentally or observationally confirmed facts. The author does not introduce to the physics any new and difficult (or entirely impossible) for experimental verification processes such as for example so called "Laval-jet" **[1]**,"Alfvén waves" **[2]**, or electrical and magnetic "short circuits" **[Dr. George Withbroe**, SEC HQ NASA**]**.

The reasoning presented below shows only the main thought, idea, which may occur helpful in answering one of the "Big Questions" of astrophysics. This description completely omits the whole problem of ionization and spectrum lines in the solar gas. Precise mathematical description and adequate research and measurements taking into consideration the ionization and recombination in the Sun corona gas must be carried out by the professional scientists in NASA, JPL or other who surely have much more financial possibilities and scientific experiences than the author of the present description.

THE FLIGHT OF THE SOLAR GAS TOWARDS THE SPACE VACUUM

According to the kinetic theory of gas, the mean length of the free way of particles between collisions is described by formula (1) and their mean velocity by formula (1a)

$$l = \frac{1}{4\pi\sqrt{2} \cdot N \cdot r_0^2} \tag{1}$$

$$\bar{v} = (3kT/m)^{1/2} \tag{1a}$$

and for an one-atom gas we have **[1]**

$$c_v \cdot \rho = (3/2)\, k \cdot N \tag{2}$$

where:

m = particle's mass; c_v = specific heat pro gram; N = number density [cm^{-3}];
r_0 = kinetic radius of particle's activity; k = Boltzmann's constant; ρ = density.

After calculating 'N' from (2) and substitution to (1) we obtain mean way between collisions as

$$l = 0{,}08 \cdot \frac{k}{r_0^2 \cdot c_v \cdot \rho} \tag{3}$$

From the formula (3) we see that together with decreasing gas density (ρ) the mean free way (the distance between collisions) of ions and electrons increases. With density $\rho = 10\,\mathrm{gcm}^{-3}$ (in point $r \approx 0{,}33 \cdot R_\odot$) the free way between collisions for atoms (ions) and electrons is yet relatively small

$$l < 10^{-8}\mathrm{cm}$$

In the photosphere by density $\rho = 3 \cdot 10^{-7}\mathrm{gcm}^{-3}$ we obtain

$$l \approx 0{,}033\mathrm{cm}$$

It is already a very big distance in comparison to the radius of atoms which is of order of magnitude 10^{-8}cm. Few hundreds of kilometers above the visible surface of the Sun, by the gas density $\rho = 3 \cdot 10^{-8}\mathrm{gcm}^{-3}$ the mean distance between collisions of particles reaches a huge value of 1cm(!). Here we must remember that the formulas (3) and (1a) describe only the mean distance and mean velocity between collisions of ions and electrons. The whole spectrum of these parameters in the solar gas, as Maxwell's distribution shows it, also contains smaller but either much bigger values. Formulas (1) and (1a) show that both the mean distance between the collisions and mean velocity of thermal movements is much bigger for electrons than for ions (atoms), because from the physical parameters of electrons and ions it appears that:

$$r_{oe} \ll r_{o(ion)} \tag{4}$$

$$m_e \ll m_{(ion)} \tag{4a}$$

m_e, r_{oe} – mass of electrons and their kinetic radius of activity,
$m_{(ion)}$, $r_{o(ion)}$ – mass of ions and their kinetic radius of activity

Formula (3) shows one more very important feature of Sun's atmosphere. It is the anisotropy of thermal movements of the solar gas particles. Let's investigate the situation of a particle in any point 'x' of Sun's atmosphere. Any free particle of Sun's atmosphere is situated "above" the area of higher density ρ_1 and "below" the area of lower density ρ_2

$$\rho_1 > \rho_x > \rho_2 \tag{5}$$

In connection with formula (3) it means that for each of the electrons and atoms in the solar gas the free way between collisions is the longest towards the lowest density. In other words, each atom and electron has the biggest scope of movement in direction "from the Sun towards the space vacuum". It is an anisotropy similar to that of photons moving from the Sun's interior to its visible surface. As it is known, both atoms and electrons move in a gas with different velocities as we see it in Maxwell's distribution.

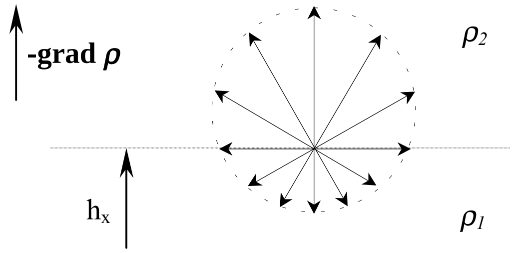

Fig.1: Distribution of length of the free distance between thermal collisions for atoms and electrons in any point 'x' on the height h_x above the surface of the Sun.
-grad ρ - direction of density's decrease in the Sun's atmosphere

Therefore the fact that in consequence of the above described anisotropy of thermal movements the furthest and the fastest move away from the Sun the fastest i.e. the hottest atoms and electrons, is only a logical consequence of basic rules of dynamics.

This anisotropy of thermal movements causes that the Sun "pumps out" to its chromosphere and corona the fastest i.e. the hottest atoms and electrons from the end of Maxwell's distribution. This fact causes that thermal motions which in the Sun's interior are yet almost completely isotropic, together with the decrease of the density in the chromosphere they become more and more directed. The most probable, privileged movement's direction of particles is the direction from the heat source (Sun) towards the space vacuum (Fig.1). This effect is clearly visible in series of SOHO pictures which show CMEs (Coronal Mass Ejection) of the present cycle of sunspots. Series of pictures of the same CME show that the front of the explosion moves faster and faster during removal from the surface of the Sun. At first this phenomenon seems to be contradictory to the basic laws of mechanics. This contradiction disappears if we consider that on the basis of the anisotropy of the thermal motions in diluting gas the fastest atoms and electrons overtake the slower ones. From the side of the space vacuum there is no material medium that would decelerate the movement of the particles flying into the space vacuum.

In this moment it must be reminded that gas' temperature parameter is defined in physics as a parameter proportional to the mean kinetic energy of particles in the examined area.

$$\bar{E}_K = \frac{m \cdot \bar{v}^2}{2} = 3 \cdot \frac{1}{2} kT \tag{6}$$

$\bar{E}_K$ – mean kinetic energy of particles
$\bar{v}$ – mean velocity of thermal movements
k – Boltzmann's constant
T – temperature

With such way of describing temperature and kinetic energy as it is shown in formula (6) individual features of individual particles disappear. In gas described only with mean thermal velocity of particles and gas' constants individual atoms or electrons do not exist anymore. Only an amorphous area of gas described with gas' constants exists. Maxwell's distribution of velocities remains as "presumably insignificant" on the edge of considerations. This reasoning is correct but only in case of closed gas area in which we can assume that thermal movements of the particles are quasi-isotropic, which means that none of the directions of collisions is privileged. In the case of gas area that from one side is opened to the space vacuum the assumption of isotropy of thermal movements is a simplification way too big. Thermodynamic considerations look a bit different if we present the mean kinetic energy of particles as the arithmetical average from the sum of kinetic energy of all particles.

$$\overline{E}_K = \frac{1}{2} \cdot \frac{\sum_{k=1}^{N} (m_k \cdot v_k^2)}{N} \tag{7}$$

$$N = N_e + N_H \tag{7a}$$

N_e, N_H – number of electrons and atoms in volume *dV* of Sun's atmosphere

The mathematical final result is the same but in the formula (7) we see each particle as an individual with its mass and velocity. This description is indispensable in case of gas diluting in direction of the space vacuum. Together with the decreasing pressure and increasing anisotropy of thermal movements the solar gas becomes more and more similar to billiard balls thrown into outer space. With the increase of distance from the Sun, the collisions' angle between ions and electrons became smaller and smaller as it would take place in case of macroscopic objects.

Let's analyze now the course of the basic parameters i.e. pressure, density and temperature in the Sun's atmosphere. The figure below (Fig.2) comes from a book **[1]** "PHYSIK DER SONNE UND DER STERNE" (H. Sheffler, H. Elsässer; ISBN 3-411-14172-7). Black lines in this picture come from the original, the red parts are added by the author of the here presented considerations. In the left of figure (Fig.2) (from point '0' to point '1' on the x-axis) the pressure, density and temperature in the Sun's atmosphere decrease as it is described by the laws of thermodynamics. In the lower layer of the chromosphere (from the level '1') the temperature starts to increase, against our expectations. The red, dashed line in the Fig.2 shows such course of temperature as should exist in the chromosphere and the corona according to the astrophysicists' expectations. As we can see in the chromosphere between the points '1' and '2' the temperature of solar gas increases relatively slow. From the lower boundary of the transitional layer (point '2') the temperature of the corona starts increasing rapidly and reaches at the point '3' the value above 1000 000ºC.

The parameters of the solar gas on the height '1' and '2' above the visible surface of the Sun obviously play a key role in the temperature distribution in the chromosphere and Sun's corona. As we can see, the temperature from the Sun interior to the point '1' decreases together with the pressure and density. It means that the thermal motions of atoms and electrons are to this level quasi-isotropic. With the density of the gas on the height of the point '1' the free way (distance) between the collisions is already so big for the electrons that the solar gas becomes for them thermal thin (transparent). It means that the fastest (hottest) electrons from the end of Maxwell's distribution are able with no bigger obstacles overcome the gravity force of the Sun and move towards the direction where they have the greatest scope of movement. It is the direction of decreasing pressure i.e. direction "towards the space vacuum".

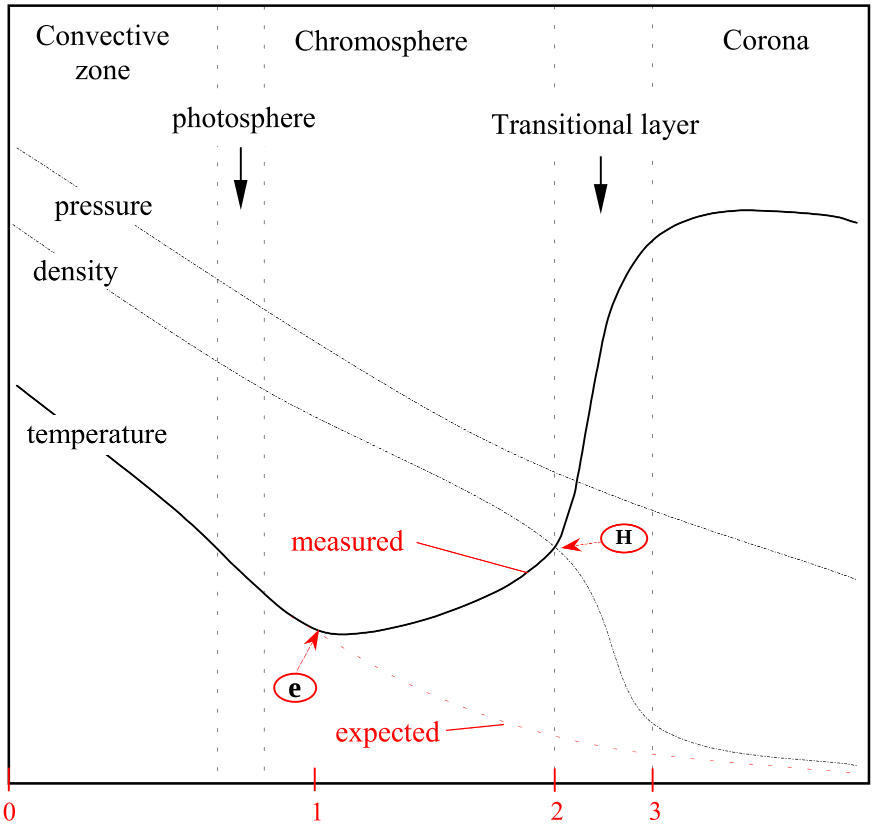

Fig.2: Qualitative courses of pressure, density and temperature in the Sun's atmosphere (according to **[1]**; Fig. **V.24**); (black lines – original; red lines – T. Tumalski)
e – the beginning of the escape of the fastest electrons by the parameters of the gas in the point '1'
H – the beginning of the escape of the fastest hydrogen atoms by the gas parameters in point '2'

On the height of the point (1) there begins in the solar gas a process that is very similar to the initial boiling of two liquids mixture which have different boiling temperatures. The fastest (the hottest) electrons have above the point "1" such a big scope of movement that they start to "boil" and "evaporate" i.e. they lift their kinetic energy to the upper layers of the chromosphere. In the chromosphere there work two parallel thermodynamic processes:

- first is the decrease of the density and the pressure of the solar gas together with the increase of the height
- second process is the "boiling and evaporating up" i.e. in the direction of the space vacuum of the fastest electrons from the end of Maxwell's distribution

Here we must come back to the description of temperature as a mean kinetic energy of gas according to the formulas (7) and (7a). Big difference of the rest mass between electrons and atoms causes that the density of gas in the chromosphere depends mainly on the concentration of atoms. Smaller density of the chromosphere gas with the increase of height means then the decreasing concentration of atoms. On the other hand, the "evaporation", i.e. the escape of the hottest electrons to the higher layers of the chromosphere causes that the ratio of the number of the fast electrons 'N_e' to the number of ions (atoms) 'N_H' (formula (7a)) increases together with the height. In the graph Fig.2 we can see that the increasing number ratio N_e/N_H has no influence on the density of gas between the points '1' and '2'. But the kinetic energy of the electrons, which is dependant on their velocities' square, has a considerable influence on the value of the mean kinetic energy of particles (i.e. temperature) in the layers of the chromosphere above the point '1'. With the sufficiently intensive inflow from the lower layers of the hot electrons, their kinetic energy causes that the mean kinetic energy of the gas particles of the middle and higher layers of the chromosphere increases. The temperature of the chromosphere then increases together with the increasing ratio N_e/N_H, while the gas density decreases because of decreasing atoms concentration 'N_H' . The fastest electrons raising to the upper layers of the chromosphere collide with other atoms, ions and electrons and transfer their kinetic energy. The increasing temperature causes the increase of the degree of ionization of the chromosphere's gas. The increasing gas' ionization therefore means the increasing number of free and "boiling" electrons. This positive cause-consequence coupling causes acceleration of the ratio's N_e/N_H increase.

Table 1: Model of the middle layers of the chromosphere of the quietly Sun, according to J.E. Vernazza, E.H. Avrett and R. Loeser (1981). τ_{5000} means optical depth by λ=5000Å. The point zero of the height scale is specified by $\tau_{5000}=1$. The visible surface of the Sun lies by the height h=300 km. N_H and N_e mean the numerical density of hydrogen and the free electrons. [according to **[1]**; **Tab.V.11** (page 422)].
The blue column of the ratio N_e/N_H calculated and added to the table by T. Tumalski.

h [km]	τ_{5000}	T[°K]	$N_H[cm^{-3}]$	$N_e[cm^{-3}]$	$\boldsymbol{N_e/N_H}$
0	1	6420	$1{,}2 \cdot 10^{17}$	$6{,}40 \cdot 10^{13}$	$5{,}33 \cdot 10^{-4}$
250	$2{,}7 \cdot 10^{-2}$	4780	$2{,}30 \cdot 10^{16}$	$2{,}70 \cdot 10^{12}$	$1{,}17 \cdot 10^{-4}$
515	$1{,}5 \cdot 10^{-4}$	4170	$2{,}10 \cdot 10^{15}$	$2{,}50 \cdot 10^{11}$	$1{,}19 \cdot 10^{-4}$
980	$9{,}1 \cdot 10^{-6}$	5925	$3{,}10 \cdot 10^{13}$	$1{,}00 \cdot 10^{11}$	$3{,}23 \cdot 10^{-3}$
1515	$2{,}4 \cdot 10^{-6}$	6370	$1{,}00 \cdot 10^{12}$	$6{,}50 \cdot 10^{10}$	$6{,}50 \cdot 10^{-2}$
1990	$5{,}9 \cdot 10^{-7}$	7160	$1{,}00 \cdot 10^{11}$	$3{,}90 \cdot 10^{10}$	$3{,}90 \cdot 10^{-1}$
2104	$2{,}9 \cdot 10^{-7}$	9500	$5{,}20 \cdot 10^{10}$	$3{,}70 \cdot 10^{10}$	$7{,}12 \cdot 10^{-1}$
2200	$1{,}4 \cdot 10^{-7}$	24000	$1{,}90 \cdot 10^{10}$	$2{,}00 \cdot 10^{10}$	1,05
2298	$3{,}7 \cdot 10^{-8}$	141000	$3{,}20 \cdot 10^{9}$	$3{,}80 \cdot 10^{9}$	1,19
2543	0	447000	$1{,}00 \cdot 10^{9}$	$1{,}20 \cdot 10^{9}$	1,20

Table 1. shows model of the middle layers of the chromosphere of the quietly Sun (according to J.E. Vernazza, E.H. Avrett and R Loeser (1981)). The basis of these calculations were the measurements of emission lines and continuum in extreme ultraviolet taken by spacecraft *Skylab*. By these calculations the authors applied model of atom with 12 admissible energetic levels. The column N_e/N_H (calculated and added to the table by T. Tumalski) shows ratio of the numerical density of free electrons to the density of hydrogen atoms (ions) in the chromosphere.

Comparison of the numeric values from the Table 1 does not yet show clearly the connections and relations between the parameters of the chromosphere gas. Only the presentation of course of the parameters in the graph shows the whole dynamics of the connections between the numerical ratio N_e/N_H and the temperature of gas in the chromosphere. In the graph of the measurements of the spacecraft *Skylab* (Fig.3) we can see that the temperature of photosphere and lower layers of the chromosphere decreases similarly as the ratio N_e/N_H. On the height of the point '1' the temperature and the density of the chromosphere gas reach such values by which starts the "boiling" of free electrons. The fastest electrons evaporate towards the space vacuum knocking out the electrons from the orbits of other hydrogen atoms. As we can see, above the point '1' the ratio N_e/N_H starts increasing rapidly. This rapidly increasing N_e/N_H is the reason of the increase of the mean kinetic energy of the particles, i.e. chromosphere temperature.

By the chromosphere gas parameters on the height of point '2' the ratio N_e/N_H reaches the value of $N_e/N_H \approx 1$ and does not increase any more. It means that this parameter reaches on the level of point '2' level of saturation because the probability of ionizing collisions of the electrons and atoms is smaller. The consequence of saturation of the ratio N_e/N_H is the fact that the further increase of the temperature of chromosphere on the basis of N_e/N_H is no longer possible. On this height the free way is so long for the electrons that the fastest of them fly away without any further collisions towards the space vacuum.
With the decreasing gas density on the level of the point '2' (Fig.2 and Fig.3) the mean distance between the collisions becomes for the hydrogen atoms so big, that the chromosphere gas becomes for them, on the side of the space vacuum, thermally thin, "transparent". The fastest atoms and ions from Maxwell's distribution have on the side of space vacuum so big scope of movement that they start escaping from the Sun towards the space vacuum. On the basis of the above described (Fig.1) anisotropy of thermal movements the fastest and the furthest move away from the Sun the fastest i.e. the hottest ions and atoms. As we can see in the Fig.2 the acceleration of corona gas' temperature increase (point "**H**") begins at the same height (2) at which the curve of chromosphere gas' density starts rapidly sinking. It is the proof that the escape of the hottest (fastest) atoms from the end of Maxwell's distribution is the cause of that rapid increase of Sun's corona temperature and also the decrease of the chromosphere gas' density. It is the same mechanism which from the height of point (1) "pumps out" the hottest electrons to the upper levels of chromosphere and causes between its points '1' and '2' increase of its temperature. The only difference is

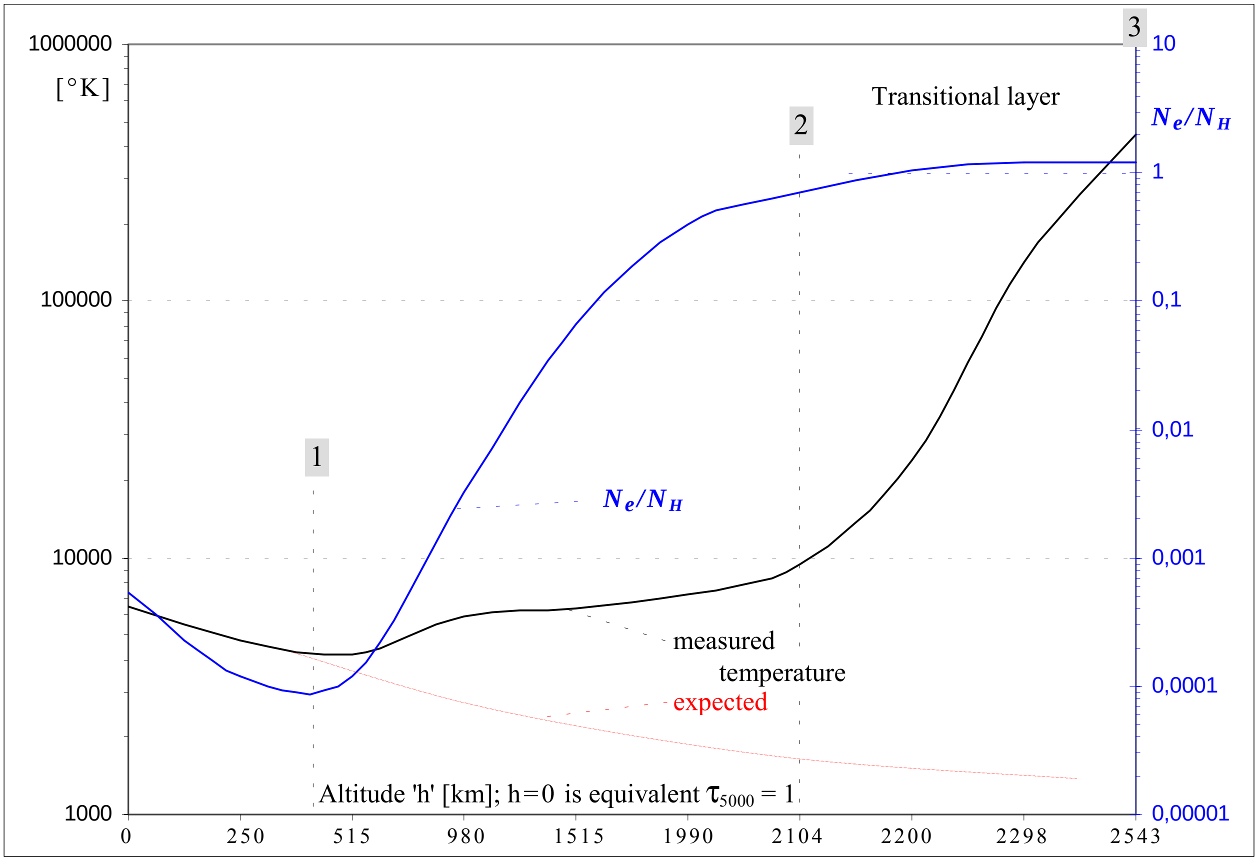

Fig.3 The courses of temperature and ratio of numerical density of free electrons to density of hydrogen atoms N_e/N_H in the chromosphere of the quietly Sun according to the data received from the *Skylab* spacecraft (Table 1.); (J.E.Vernazza, E.H. Avrett and R. Loeser (1981))
The points '1','2' and '3' stand for ca. the same heights as in the graph **Fig.2**.

that above the point (2) the hydrogen atoms do not have on the side of space vacuum any physical obstacle that would absorb their kinetic energy and stop their escape into the space vacuum. The only force that above the point '2' prevents the electrons' and atoms' escape from the chromosphere and the corona is the gravity force of the Sun. The above described anisotropy of thermal movements causes that the hydrogen atoms on their way from the heights '2' to '3' (Fig.2) are directed away from the Sun and then escape without any obstacles into the space vacuum. Because of the fact that the atmosphere of the Sun is opened from the side of space vacuum, between the heights '2' and '3' there takes place spatial selection of the particles according to their velocity on Maxwell's distribution and their direction of movement. Those of the particles which do not have the sufficient velocity "away from the Sun" are turned back to the Sun and only the fastest of them fly away into the space vacuum.

That is why above the point '3' we can find only the fastest, i.e. hottest particles of Sun's atmosphere. Every hydrogen atom remains as long in the transitional layer as after sufficiently strong collision under the proper angle flies into the space vacuum as a particle of the solar wind.

This "final collision" is the final thermodynamic contact of the Sun matter atoms with their mother star and subsequently the beginning of their journey through the infinite Universe.

THE FINAL CONCLUSIONS

The proof for that the fastest electrons transmit their kinetic energy to the upper layers of the chromosphere are the X-ray photos of the Sun. As it is known the X-rays arise during a rapid braking of the fast electrons (this phenomenon is known for over a hundred years and was sufficiently well examined and described). Therefore the areas of an intensive X-radiation in the Sun's atmosphere prove that in these regions there takes place a rapid braking of the fast electrons. In the X-ray photos of the quietly Sun it is clearly visible that the most intensive X-rays exactly come from the layers between the points '1' and '2' (Figs 2. and 3.) i.e. on these heights where the "boiling" electrons escape up and initially increase the temperature of the Sun's chromosphere. This fact is a confirmation for the above described process of "boiling and pumping out" the fast electrons to the chromosphere. The fast electrons from the end of Maxwell's distribution flying into the space vacuum, collide with the atoms, ions and slow electrons and emit during that process the X-rays.

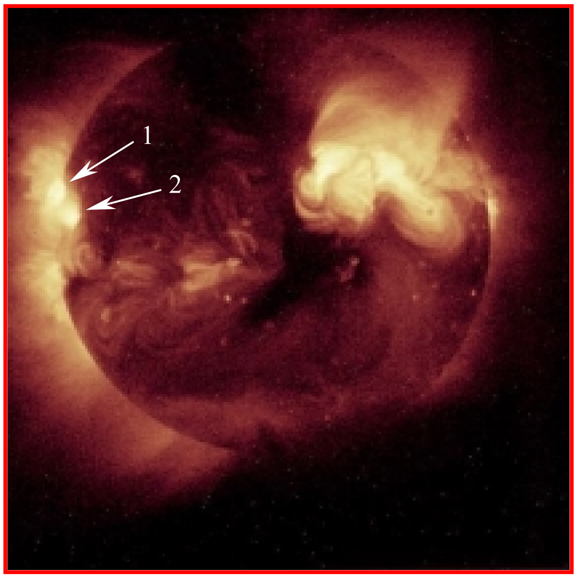

Fig 4: This is an X-ray image of the Sun obtained on February 21, 1994. The brighter regions are sources of increased X-ray emissions.
(Calvin J. Hamilton, and Yohkoh)

The Lorenz force that acts on the electric charges moving in a magnetic field causes that the trajectories of the electrons and ions are wind to the opposite directions round the lines of the magnetic field. This fact intensifies the above described (Fig.1) anisotropy of thermal movements of electrons and ions. The magnetic anisotropy of thermal movements causes that the probability of the collisions of ions and electrons is far bigger in the magnetic field of the sunspots.

In the picture Fig.4 the arrows (1) and (2) show the X-rays above the pair of *P-N* sunspots. With this angle of observation of the sunspots we can see that the most intensive X-radiation is emitted from the lower layers of the Sun chromosphere. Therefore the intensive X-rays in the chromosphere are a proof that in these areas takes place an intensive initial warming (the height between the points '1' and '2' in the Fig.2 and Fig.3) of the Sun's chromosphere by the intensive escape of the hot electrons. The same phenomenon we can see under a another point of view in the eastern part of that photo (Fig.4).

The above described intensive escape of the hot (fast) electrons and ions in the magnetic field of the sunspots causes that the temperature of corona above the active regions is much higher (over 2,000,000°C) than the temperature of coronal holes (ca. 1,000,000°C). From the above described mechanism we can draw a conclusion that after the disappearance of the magnetic field of the sunspots the hot chromosphere's gas "evaporates" into the space vacuum. Because the fast electrons and atoms have been "pumped out" from the lower layers to the chromosphere and the corona, then after the "evaporation" of the hot chromosphere's gas in the place of the active regions the mean kinetic energy of the particles (i.e. temperature) of the chromosphere and the Sun corona decreases. The lack of the fastest electrons is also the cause of decrease of the intensity of X-radiation. Therefore, it means that after the disappearance of the magnetic field of the sunspots the active regions change into the coronal holes. Confirmation of this mechanism is the, observed already in 1973 by *Skylab*, correlation of periods of fast solar wind with the rotation of coronal holes. Long-term observations of the active regions of Sun's atmosphere will certainly prove the unmistakable space correlation between the active regions and following them coronal holes. The process of heating and evaporating of the gas above the active regions of the Sun's atmosphere is therefore very similar to the well known in physics process of liquids' boiling. The only difference is that the solar gas is open from the side of the space vacuum.

As we can see, the increase of temperature of chromosphere and the Sun corona is not exactly the same process of heating, i.e. providing energy to the system, that we know from physics. It is a process of pushing out into the space vacuum the particles having the biggest velocity, i.e. the biggest kinetic energy in a gas opened from one side to the space vacuum.

NOTE:

Precise laboratory measurements will certainly show that the temperature very close to the surface of hot, intensively evaporating liquid is higher than the temperature inside the liquid's volume itself. It does not mean of course that in the liquid exists some mysterious mechanism heating the vapors of the liquid near to its surface. This fact will only prove the principle that only the fastest (hottest) particles from the end of Maxwell's distribution can overcome the surface tension of the liquid and get out above its surface. In the effect, the mean kinetic energy of particles (i.e. temperature) just above the surface of the liquid can be higher than inside the liquid's volume itself. This effect will probably be enhanced by the decrease of the pressure above the surface of the liquid.

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