Review Article
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On the temperature of the solar corona

Abstract

It has long been considered that the high temperature of the solar corona, inferred from the presence of highly ionized atoms such as Fe^{XIV}, is caused by various heat transfer processes from the photosphere. In this paper, it is suggested that the neutral hydrogen layer, containing Fe atoms, of the corona, are *ionized* by the impact of energetic current carrying electrons along loops of magnetic field lines. It is suggested that current-carrying electrons are accelerated by the double layer; the corona consists of a large number of magnetic loops. It is shown that the current of intensity of about $1\mu A/cm^2$, consisting of 10 Kev electrons accelerated by the double layer, could provide the ionization rate of 1.8 x 10^4/cm^3 in the corona along the loops. Thus, the corona could not be in a thermal equilibrium, so that the temperature of the corona may not be inferred from what the ionization potential of highly ionized atoms suggests. It is shown also that a dynamo process of the photosphere can generate the needed field-aligned currents. Further, the above estimated ionization rate can supply the solar wind.

Keywords: solar corona, ionization rate, energetic electrons double layer

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Introduction

After the high temperature of the solar corona was discovered in the 1940s in terms of emissions from highly ionized Fe and other atoms, there have been a very large number of attempts to explain the coronal high temperature; Aschwanden[1] listed more than 40 theories of coronal heating. In the most recent review, Van Doorsselaere et al.[2] summarized the difficulties of heating the corona by MHD waves. In many cases, researchers are trying to explain both the high temperature of the corona and causes of the solar wind together.

The temperature of the photosphere is 0.5 eV, corresponding to the temperature of 6000K, while the coronal temperature of 2x10^6 K, corresponds to 170 eV (the ionization of Fe^{XIV} requires 280 eV).[3,4] Another important fact is that the corona is composed of a large number of loop structures in addition to the stratified layer (cf. Aschwanden[1]).

Ionization by a high energy electron beam

As mentioned in the introduction, it seems to be very difficult to find plasma or wave processes to heat the coronal atoms to more than 10^6 K or more than 200 ev.

However, energetic current-carrying electrons of 1 Kev can ionize only hydrogen atoms, but also Fe atoms. An electric field along magnetic field lines can accelerate current-carrying electrons in a magnetized plasma. Such a possibility requires the presence of a double layer in a magnetic field-aligned electric current.[5] The coronal situation is somewhat similar to the high temperature of the ionosphere. In the aurora, oxygen atoms are ionized. Their ionization potential is 4 ev, the corresponding temperature being $4.5\ x\ 10^{4^\circ} K$, but the ionosphere is not heated from below. The oxygen atoms are ionized by the impact of energetic electrons in the field-aligned currents, which cause the aurora. These electrons are accelerated by the double layer above the ionosphere.

In fact, the presence of an electric field associated with the double layer along magnetic field lines was originally suggested by Alfven[5] on the ground that the magnetospheric electric current system has to close itself through the ionosphere (current continuity) by penetrating into the conductive ionosphere at an altitude of 110 km from the magnetosphere.

The understanding of the nature of the double layer is still incomplete, but its presence (a U-shaped potential structure) in field-aligned currents is observationally confirmed by a number of satellite observations in auroral research. In the earth's auroral conditions, various observed values related to the double layer are summarized by Karlsson:[6,7] Field-aligned potential drops of the order of 6 kV or more, field-aligned currents of $10^{-1} - 10^{1}\mu A/cm^2$, and the acceleration of magnetospheric electrons from 300 eV to 10 KeV and more; theoretical estimated values of the double layer are 10 KV per 1 km between 0.5-2.0 Re above the ionosphere (Re = the earth's radius).

The equation for the ionization rate by a beam of energetic electrons in the ionosphere is given by cf. Rees:[8]

$$q = F\ E\rho d\ /\ 30\ ev\ \ /cm^3 s^{-1}.$$

A typical set of observed values for the ionosphere at the height of 110 km are:

F= electron flux (10^7/cm^{2}s), corresponding to $0.1\mu A$,

E = electron energy (10 Kev),

N= atmospheric density (10^{12}/cm^3)

ρ = mass density (1.6 x 10^{-12} g = 10^{12}/cm^3 x 1.6 x 10^{-24}g),

d= penetration depth (10^6 cm),

RE^2= effective range (5.34 x 10^2 g/cm^2).

Based on these values, the ionization rate q is estimated to be

$$q = \ 1.9\ x10^3\ /\ cm^3 s,$$

and in the equilibrium condition, the electron density $Ne\ = \ddot{O}(qN/h)\ =\ 1.1\ x\ 10^9\ /\ cm^3$, where $h\ =\ 1.6\ x\ 10^{-6} cm^3\ /\ s$ is the recombination rate.[3] The above numbers are commonly adopted ones (Rees[8]; section 3.3 and figure 3.3.3, p.41).

Coronal ionization by energetic electrons

For the corona, we consider a loop of magnetic field lines or tube, which rises from the photosphere and penetrates into the corona (and back to the photosphere) and compute *the ionization rate by field-aligned current along the magnetic tube of* $1\mu A$.

The same equation of the ionization rate q should be applicable in the corona with the same set of parameters, except there are some uncertainties in the adopted values of the parameters. Considering the electron flux F corresponds to

$1 \mu A / cm^2$, accelerated electron energy by the double layer E (10 Kev), number density $N = 10^{12} / cm^3$ at the height of 10^3 km [corresponding to $\rho = 1.6 x 10^{13} g$ (Aschwanden[1] (figure 1.19, p.24); d [corresponding to the stopping distance] is assuming to be 10^6 cm on the basis of the ionospheric situation. Thus, the required parameters are:

$F = 6.2 x 10^8/cm^2 s$, corresponding to $1 mA/cm^2$

$E = 10$ Kev,

$N = 10^{12}/cm^3$

$\rho = 1.6 x 10^{-13} g$ ($= 10^{12}/cm^3 x 1.6 x 10^{-24} g$),

$d = 10^6 cm$

$RE^2 = 5.6 x 10^2 g/cm^2$.

Based on the above values, the ionization rate q is estimated to be:

$q = 1.9 x 10^4 / cm^3 s$,

and in the equilibrium condition, the electron density is $Ne = Ö(qN/h) = 1.1 x 10^{10} / cm^3$ in a magnetic loop.

These values of q and Ne are within acceptable range. Further, the above values may be enough to supply the solar wind (10^2-$10^3/cm^3 s$); (cf. Lee and Akasofu).[8] If the ionization would occur at a higher level, it may be difficult to supply the solar wind. It is difficult to speculate where the expected double layer forms along the loop; there is a prominent discontinuity of the electron density at about the height of 10^3 km from the photosphere, where the electron density varies from $10^{10}/cm^3$ to 10^9 cm^3 in a short distance in the model by Aschwanden,[1] (his figure 1.19, p.24); the formation of the double layer may partially depend on the electric current discontinuity. The middle level of the corona is chosen by keeping in mind these factors.

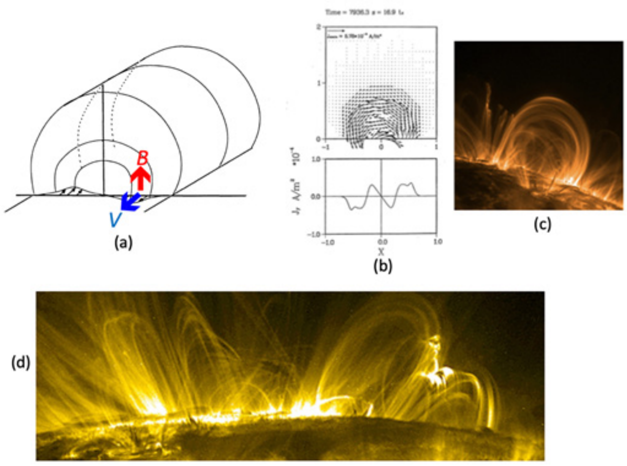

Figure 1 (a) A model of photospheric dynamo.[9] (b) The field-aligned currents (0.5×10^{-4} A/m²) resulting from the dynamo along the magnetic arcade configuration in (a) [Courtesy of G. S. Choe]. (c,d) Typical magnetic loops in the corona (NASA Corona Collection).

Field-aligned currents produced by a dynamo process

The intensity of field-aligned current has not been well known in the corona. However, it is quantitatively estimated for a photospheric dynamo process for a moderate flare (a typical two-ribbon flare); it is estimated to be $5 x 10^{-5} A / m^2 (5 x 10 \mu A / cm^2)$. The dynamo process is considered with a set of $B = 6$ Gauss and the speed V of 2 km/s along the neutral line in the photosphere.[9]

Figure 1 shows both the distribution and the intensity of the field-aligned current for such a two-ribbon flare; the field-aligned currents flow into both sides of the two ribbons in this case. Much weaker dynamo process is expected to occur in the photosphere (for example, mini-flares), so that the field current intensity of 1 $\mu A / cm^2$ along magnetic field lines or tubes may be sufficient in ionizing the corona.

Conclusive remarks

It is suggested that the corona is ionized by the impact of energetic electron beams accelerated by the double layer, rather than various heat transfer processes from the photosphere. The double layer is likely to be generated in the field-aligned currents along loops of magnetic field lines, producing the loop structure of the corona. The impacting electrons can ionize Fe^{XIV} atoms. On the basis of a model of the corona, the ionization rate is enough to supply the solar wind.

Thus, if the corona is not in a thermal equilibrium, the high temperature of the corona inferred from the presence of highly ionized atoms may have to be reconsidered. This is a very tentative and preliminary attempt, but it is hoped that such a possibility should be pursued.

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Conflicts of Interest

None.

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