On the High Temperature of the Corona

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Key points

- The ionization of highly ionized coronal atoms is caused by

energetic current-carrying electrons, accelerated by a double

layer.

- The current is generated by a photospheric dynamo process.

Abstract

It is suggested that the high temperature of the corona, 2 x 10^6K, recognized by the presence of Fe^{XIV} is caused by the ionization of accelerated electrons by a double layer. Under the condition of magnetic field-aligned currents (along magnetic loops in the corona) of intensity of about 0.001A (10^3 A) and 1 Kev electrons accelerated by the double layer, the ionization rate is estimated to be 6.3x10^8/cm^{3}s in the middle level of the corona, where the density of hydrogen atoms is about 10^{11}/cm^3 at the height of 2 x 10^3 km. A dynamo process of the photosphere provides the field-aligned currents. A double layer might be formed in a prominent discontinuity of the electron density of about the height of 2 x 10^3 km, where the above estimates are made.

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Plain language summary

The high temperature of the corona by heat energy from the photosphere seems to be difficult. Thus, the ionization process by energetic electrons is proposed. A dynamo process in the photosphere produces field-aligned currents along magnetic loops in the corona, in which a double layer (an electric field) along magnetic field lines might form. The resulting ionization rate is semi-quantitatively estimated.

Keywords: solar corona. coronal temperature. double layer

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1. Introduction

After the high temperature, 2x10^6 K, of the solar corona was discovered in the 1940s in terms of emissions from highly ionized Fe^{XII} atoms (ionization potential, 250 eV) others, there have been a very large number of attempts to explain the coronal high temperature in the past (cf. Van de Hulst, 1953; Zirn, 1988).

However, in one of the most recent reviews examining various past efforts, Van Doorsselaere at al. (2020) summarized the

difficulties of heating the corona by MHD waves.

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In the past, it had been considered that highly ionized ions must

be caused by the ionization of the corona by energetic

electrons (Stix, 2002), but the responsible process of the acceleration of electrons in the coronal environment have not been known.

In this paper, we suggest a field-aligned current system along

coronal magnetic loops, which is driven by a photospheric

dynamo process for the field-aligned currents; field-aligned currents are essential in developing a double layer, which can accelerate both electrons and ions.

1. **Acceleration of electrons of auroral electrons**

The coronal situation is somewhat similar to the ionospheric one. The auroral green line oxygen atoms (their excitation potential 4 ev, the corresponding temperature being 4.5 x 10^{4° K) is caused by the excitation of oxygen atoms by secondary

electrons, which are produced by the ionization of energetic

current-carrying electrons in the field-aligned currents. They

are accelerated by the double layer in the magnetosphere-

Ionosphere coupling circuit.

However, the ambient temperature of the ionosphere is known

to be at most 2000K, not 4.5 x 10^4 K. This ambient high

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temperature is caused by the additional ionization by solar X-rays in daylight hours.

In auroral processes, the presence of the electric field of the double layer, consisted of a U-shaped potential, along magnetic field lines was suggested by Alfven (cf.1981, 1986) on the ground that current-carrying electrons cannot cause the aurora

without being accelerated (from 100-300 ev in the magnetosphere to more than 10 KeV to penetrate into the

ionosphere) and that the magnetospheric current

system has to close (current continuity) by connecting to the ionospheric currents.

In auroral research, the presence of a U-shaped potential structure in field-aligned currents is observationally well confirmed by many satellite observations. In the earth's auroral conditions, various observed values related to the

double layer are summarized by (Karlsson, 2012): Field-aligned potential drops of the order of 6 KV or more, field-aligned currents of 10^{-1}-10^{1} A/cm^2, and the acceleration of magnetospheric electrons from 300 eV to 10 KeV and more, an

estimated thickness of the double layer 10 KV per 1 km, located 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 1989):

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q (cm^3s) = F E d/ (RE^2 x30 ev).

A typical set of observed values for the ionosphere by assuming that the field-aligned current intensity of 1 A and the double

layer of 10 KV potential drop:

The ionization rate q at the height of 110 km is:

F= electron flux (10^8/cm^2s),

E = electron energy (10 Kev),

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

d= depth/distance (10^7 cm),

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

q= 1.9 x10^6/cm^3s,

where the number density is taken to be 10^{11}/cm^3.

This value of q is well within the accepted values Rees, 1989).

1. **Coronal ionization by energetic electrons**

In the past, a double layer has been considered for solar flares

and its effect on coronal processes (Li et al., 2013, 2014).

However, no estimate of the ionization rate by a double layer

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has been made for a given current intensity and its potential drop.

Here, we consider a loop of magnetic field lines in the corona as the circuit.

The ionization rate of the middle level of the corona by field-

aligned currents of 0.001 A (10^{3} A), supposing that the double layer provides a potential drop of 1KV:

F = 6.2 x 10^{11}/cm^2 s^{-1},

E = 1 Kev,

 = 1.6 x 10^{-13}g (= 10^{11}/cm^3 x 1.6 x10^{-24} g),

d = 10^9cm (assuming about 10^2 collisions/s),

RE^2 = 5.6 g/cm^2,

q = 6.3 x 10^8/cm^3s,

where the number density is taken to be 10^{11}/cm^3 at the height of 2 x 10^3 km (Aschwanden (2005, his figure 1.19).

1. **Field-aligned currents produced by a dynamo process**

The currents must be generated by a photospheric dynamo process. An example of the dynamo-induces field-aligned currents under a magnetic arcade is shown in Figure 1. The

dynamo process is considered here with a set of B = 12 G and the

speed of 2 km/s along the neutral line under a typical

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magnetic arcade (Choe and Lee, 1996)); the intensity of

the field-aligned currents 0.5 x 10^{-4}A/m^2 (5 x 10 A/m^2) in

this case.

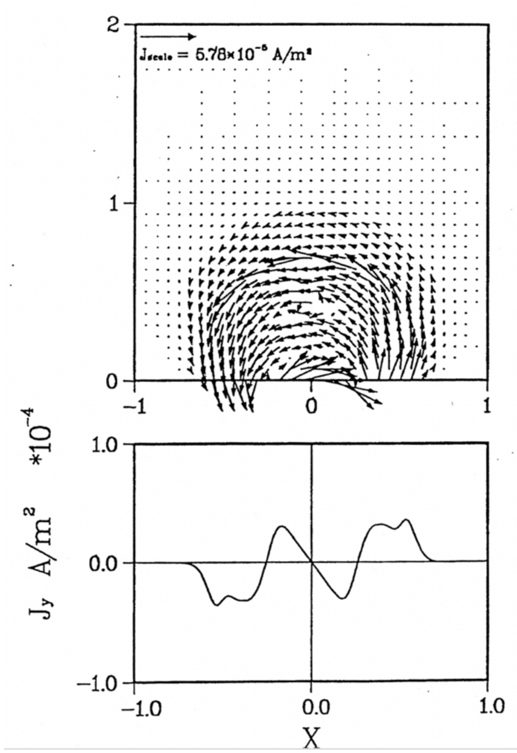

Figure 1. The distribution of the field-aligned currents associated with a dynamo under a magnetic arcade, producing a two-ribbon flare (Akasofu and Lee 2019; Courtesy of G. S. Choe).

1. **Conclusive Remarks**

Therefore, it seems that the proposed field-aligned currents along magnetic loops in the corona can ionize hydrogen atoms and Fe atoms in the middle level of the corona.

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At this point, it is difficult to speculate how and where the

expected double layer might form. One possibility is a

prominent discontinuity of the electron density at about the height of 2 x 10^3 km from the photosphere, where the electron

density varies from 10^{10}/ cm^3 to 10^9 cm^3 within almost the

same height (Aschwanden, 2005, his figure 1.19, p.24). The

above estimates of ionization rate q is made by keeping in mind this discontinuity region.

It is hoped that this paper will be useful in investigating a new

way of considering the high temperature of the *whole* corona.

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