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Research Article

# On the Ionization of Coronal Loops and Aurora

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**Abstract**

*The possibility of ionization of the solar coronal loops by energetic current-carrying electrons is investigated, since FeXII and other highly ionized atoms are brightest along looped magnetic field lines in the corona. In this paper, we consider a photospheric dynamo under a magnetic arcade as the source of field-aligned current. Assuming the current intensity of 1 μA/cm², the density $N = 10^{12}/cm^3$ in the lower corona (not too different from the auroral condition) and current-carrying electrons accelerated by the double layer 10 KeV, the ionization rate q is estimated to be $1.3 \times 10^4/cm^3s$. The result is compared with the auroral ionization, which is caused basically by the same process and is well confirmed ($1.3 \times 10^5/cm^3s$) by observations. A possible consequence of our consideration on the coronal temperature is mentioned.*

**Keywords:** Solar Corona Ionization Coronal Loop Ionosphere Double Layer

## 1. Introduction

It was in the 1940s when coronal lights are emitted from highly ionized atoms, such as $Fe^{XII}$ (the ionization potential, 280 eV), which lost 14 electrons out of 26, namely *ionization*. It has been considered that their presence is caused by a very high temperature of about million degrees. Thus, from the time of its discovery, researchers have tried to explain how the heat source of the photosphere (including Alfven waves) can cause the coronal high temperature and the ionization of the corona [1]. So far, there are 40 theories on the cause of the high temperature of the corona, so that there seems to be no generally acceptable theory yet [1].

On the other hand, it seems that the coronal ionization by current-carrying electrons has not been considered in the past (not in the list of Aschwanden).

There are at least three requirements in considering the ionization of the coronal loop in terms of current-carrying energetic electrons. They are:
(1) Photospheric dynamo as the source of field-aligned current (Section 2),
(2) Current circuit containing magnetic field lines (Section 3),
(3) Ionization rate (Section 4)

## 2. Photospheric dynamo and circuit

We consider a photospheric dynamo in a magnetic arcade as the source of field-aligned current; Figure 1.

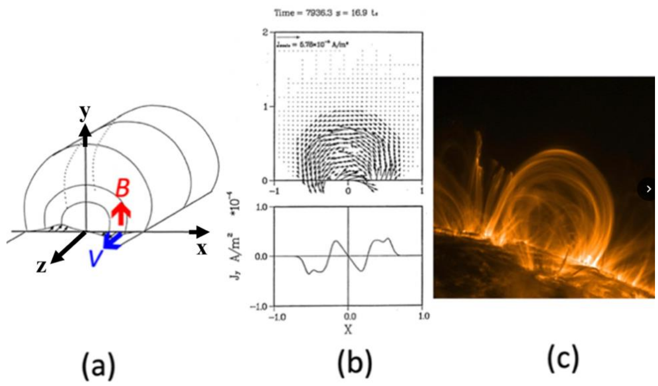


**Figure 1** (a) A model of photospheric dynamo in a magnetic arcade [2] The sear flow $V_z$ is applied in the ± z direction. (b) The field-aligned currents resulting from the dynamo along the magnetic arcade configuration in (a) [Courtesy of G. S. Choe]; this dynamo can produce field-aligned current of 0.5 A /m² (50 μ A/ cm²). (c) Typical magnetic loops in the corona (NASA corona collection).

This photospheric dynamo has been studied by Choe and Lee (1996) and Akasofu and Lee (2019) [2,3]. A sheared flow velocity is applied in the direction for the magnetic arcade. The power *P* is given by:

$$P = \int \boldsymbol{S} \cdot d\boldsymbol{A} \qquad (1)$$

*and* the Poynting vector

$$\boldsymbol{S} = (\boldsymbol{E} \times \boldsymbol{B})/4\pi \quad (2)$$

$$P = VzBzByA/4\pi, \quad (3)$$

where A is the photospheric surface area of the sheared magnetic arcade, (the area of typical two-ribbon of the emission). For example, we consider $A = 2 \times 2 \times 10^5$ km x $2.5 \times 10^4$ km $= 10^{20}$ cm$^2$ ($10^{16}$ km$^2$); and $ByBz = (15\ G)^2$ and photospheric plasma speed $V = 1.5 \times 10^5$ cm/s ($1.5 \times 10^3$ m/s), With these paramers, the power $P$ is:

$$P = 2.0 \times 10^{19}\ W. \quad (4)$$

This dynamo power is enough to produce the two-ribbon Hα emission (Svestka,1958). Our photospheric dynamo can produce also *field-aligned current* of 0.5 A /m$^2$ (50 μA/cm$^2$); Figure 1b.

For the coronal ionization, we need a much wreaker dynamo. For example, a weaker dynamo, a photospheric magnetic field (10 G) and a slow velocity (1 km/s or less), can generate field-aligned current of 1μA/cm$^2$.

*The reason for emphasizing the field-aligned current is that it can produce the necessary electric field for the ionization*. The field-aligned current in a circuit tends to produce a potential structure along magnetic field lines in order to close the circuit (Alfven, 1986). There are a large number of satellite observations of the double layer associated with auroral field-aligned currents in the magnetosphere-ionosphere situation (Figure 2). The magnetosphere-ionosphere observations have been conducted by satellites [4,5,6].

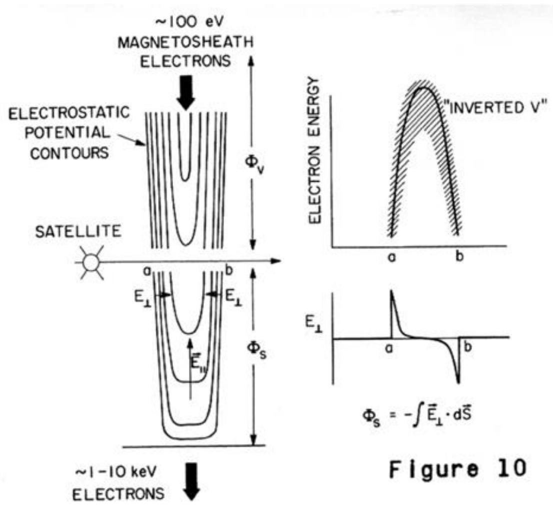


**Figure 2** Observed double layer, i1ts potential structure (Don A. Gurnett).

In the auroral situation, current carrying electrons are accelerated from 300eV to 10Kev in order to flow into the ionosphere. There is no simple acceleration process to such high energies particularly along magnetic field lines. In section 4, we assume that in our case, current-carrying. Electrons is accelerated to 10 KeV.

## 3. Circuit

As mentioned in the above, our photospheric dynamo can generates field-aligned current along magnetic field lines of a magnetic arcade. The emission from $Fe^{Xii}$ and other highly ionized atoms are brightest in the coronal magnetic loops, so that the magnetic field lines can be a part of the circuits. In fact, as Figure 3 shows, it is likely that the corona may not be a well-stratified atmosphere [1].

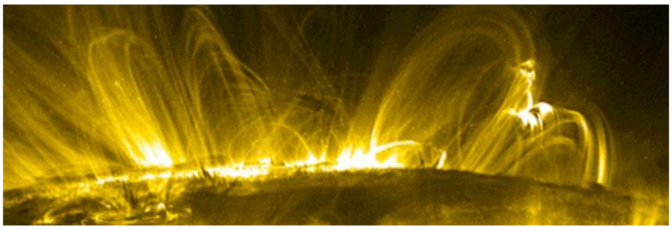

**Figure 3** Typical magnetic loops in the corona (NASA Corona Collection). It appears that the corona is basically consisted of a large number of loops, instead of a stratified atmospheric layer.

## 4. Coronal ionization by current-carrying electrons

The equation for the ionization rate $q$ by a beam of energetic electrons is given by Rees (1989):

$$q = F\varepsilon_e \rho / (\varepsilon_e^2) \times 30e\upsilon)$$

Taking electron flux ($F = 6.2 \times 10^8$/cm$^2$ s, corresponding to 1μ A/cm$^2$, electron energy ($\varepsilon_e$= 10 Kev), atmospheric density (N= $10^{12}$/cm$^3$), mass density ($\rho = 1.6 \times 10^{-12}$g/cm$^3$ (= $10^{12}$/cm$^3$ x 1.6 x$10^{-24}$ g), and effective range $R(\varepsilon_e^2) = 2.5 \times 10^{-4}$ g/cm$^2$),

the ionization rate is:

$$q = 1.3 \times 10^4/\text{cm}^3\text{s}.$$

Further, the above ionization rate $q$ can supply the solar wind. If the number of the neutral density is less than N = $10^{12}$/cm$^3$), it is not possible to supply even the solar wind, indicating that the double layer is not located in a higher level of the corona.

## 5. Auroral ionization

The above equation has been used for the *auroral ionization*. Taking the well-confirmed parameters, namely electron flux ($F = 6.2 \times 10^9$/cm$^2$ s, electron energy ($\varepsilon_e$ = 10 Kev), atmospheric density (N= $10^{13}$/cm$^3$), mass density ($\rho = 1.6 \times 10^{-13}$g/cm$^3$ (= $10^{13}$/cm$^3$ x 1.6 x$10^{-24}$ g)), and effective range $R(\varepsilon_e^2) = 2.5 \times 10^{-4}$ g/cm$^2$), the ionization rate is:

$$q = 1.3 \times 10^5/\text{cm}^3\text{s}$$

This value is well within the observed values in the ionosphere (Rees, 1989).

## 5. Possible consequences

If the ionization of atoms is partially caused by the impact of energetic electrons, one must be cautious in estimating the coronal loop temperature from the ionization potential of highly ionized atoms alone. The auroral green line (55.77nm) is excited mostly by secondary electrons of energy 4 eV; their corresponding temperature is 45000 K. On the other hand, the temperature of neutral particles is known to be 1200 K and the ion temperature is about 2000K (Walker and Rees, 1968), which are far less than 45000 K.

## 7. Conclusive remarks

Coronal photographs (such as the one in Figures 1c and 2) show that the brightest part of the corona has a loop structure. Thus, it is worthwhile to examine the ionization along magnetic field lines. Our estimate suggests that current-carrying electrons along the magnetic field lines seems to show a significant amount of ionization ($q$ = 1.3 x $10^4$ /$cm^3$s) in the coronal loop.


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## Data usage

In this paper, no new data are used. Other data are from published ones, and they are noted in the figure captions.


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