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CORONAL LOOPS HEATING IN THE ATMOSPHERE OF THE AD LEO RED DWARF

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We study the possible origin of long-lasting soft X-ray flares on the AD Leo star, which were observed onboard the Extreme Ultraviolet Explorer (EUVE) spacecraft for the period of 1993-2000 [1]. These flares have relatively long rise and decay times of the radiation intensity ($\tau_R \approx 10^4$ s and $\tau_d \approx 5 \cdot 10^3$, respectively), as well as a relatively large emission measure $EM \approx 10^{51} cm^{-3}$, which exceeds by 1–3 orders of magnitude the emission measure of soft X-ray flares on the Sun. Assuming that the radiation appears in magnetic loops and basing on the observed values of the emission measure and radiation decay time, the authors of [1] determined the typical length $\bar{l} \approx 1.5{\cdot}10^{10}$ cm, electron number density $\bar{n} \approx 3{\cdot}10^{11} cm^{-3}$, and plasma temperature $\bar{T} \approx 2.5{\cdot}10^7$ K of the loops. This paper considers plasma heating due to dissipation of the electric currents in the coronal magnetic loops of the star induced by the photospheric convection. The large inductance of the loop as an equivalent electric circuit determines the long time of the current rise in the source and explains the observed time of plasma heating and the rise time of the X-ray radiation intensity. It is shown that the parameters of the X-ray sources in the AD Leo atmosphere agree with the parameters calculated under the assumption of simultaneous emission of a great number of loops (about 50) with electric currents greater than 10^{13} A, which exceeds the electric currents in the solar coronal magnetic loops by 1–3 orders of magnitude. Such an exceeding can be related to the higher photospheric convection velocities on the late-type stars compared with the Sun.

1. INTRODUCTION

Currently, it is generally accepted that the solar corona is structured and consists of plasma-filled magnetic loops, in which the temperature and pressure vary widely [2–4]. Direct observation of the magnetic loops of other stars is not possible for now, although by using very long-base radio interferometers one can observe solar disks in some favorable cases. Nevertheless, magnetic loops are supposed to exist in the coronas of other stars, first of all, stars of the later spectral classes, and these loops are intensely studied by indirect methods, e. g., by analysis of X-ray and radio emission. For example, the authors of [1] determine the loop parameters for 44 stars of F to M spectral classes using the data on emission measure and decay time of soft X-ray radiation from Extreme Ultraviolet Explorer. The results of the studies have shown that loops with a length of up to one-half of the star radius, a plasma density of 10^{11} to 10^{12} cm^{-3}, and a temperature of 10^7 to 10^8 K can exist on all stars of the mentioned types.

The stellar-corona heating is one of topical problems in astrophysics [5, 6] and is far from solution for now. The solar corona, whose temperature is about 10^6 K, requires a heating rate of about 10^{-3} erg/(cm$^3\cdot$s). The late-type stars with corona temperatures of about 10^7–10^8 K require heating sources of still higher powers. Ohmic dissipation of electric currents flowing along the magnetic field [7, 8], tearing instability [9,

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10], micro flashes [11–13], wave dissipation [14, 15], and chromospheric plasma evaporation [16, 17] have been considered in the literature as candidate mechanisms of the corona heating. In [18], it is shown that plasma heating in the solar magnetic loops can be related to current dissipation in the magnetic loop due to ion–atomic collisions in the magnetic field, which stipulate the Cowling conductivity. It is shown that in the corona conditions the above dissipation mechanism is much more effective than the Spitzer dissipation of parallel currents and provide a plasma heating of up to coronal temperatures even with insignificant content of neutral atoms in the corona plasma. In the present paper, this dissipation mechanism is considered by analysis of flaring sources of soft X-ray radiation on stars of the later spectral classes. As an example, we study X-ray flares on the AD Leo red dwarf, which were observed onboard Extreme Ultraviolet Explorer in 1993–2000 [1]. This dwarf belongs to the M3.5V spectral type and has a radius $R_* = 0.3R_\odot$, where $R_\odot$ is the Sun's radius, a photospheric temperature of about 3400 K, and photospheric magnetic fields of about 4 kG, such that the spots cover about 60–70% of its surface [19]. Free-fall acceleration in the photosphere is equal to $g = 4.6 \cdot 10^4$ cm/s^2. The studied flares of soft X-ray radiation had relatively long rise and decay times of the radiation intensity. For example, the flare of March 1, 1993 had a rise time $\tau_\mathrm{R} \approx 10^4$ s and a decay time $\tau_\mathrm{d} \approx 5 \cdot 10^3$ s [20]. The emission measure reached EM $\approx 10^{51}$ cm^{-3}, i. e., exceeded by 1–3 orders of magnitude the emission measure for soft X-ray flares on the Sun. Assuming that the radiation appears in the magnetic loops and using the observed values of the emission measure and decay time of the radiation, the authors of [1] determined the average length of the loops $\bar{l} \approx 1.5 \cdot 10^{10}/N_\mathrm{L}^{1/4}$ cm, as well as the density $\bar{n} \approx 3 \cdot 10^{11}/N_\mathrm{L}^{1/8}$ cm^{-3} and temperature $\bar{T} \approx 2.5 \cdot 10^7/N_\mathrm{L}^{1/4}$ K of the plasma in the loops. Here, N_L is the number of magnetic loops contributing to the intensity of soft X-ray radiation and the observed emission measure. In the estimation of average values, it was assumed that the thickness-to-length ratio of the loops was 0.1. This ratio is also typical of the flaring magnetic loops. In the present paper, we consider plasma heating in the coronal magnetic loops of a star as resulting from dissipation of the electric currents induced by photospheric convection. High inductance of the loops as equivalent electric circuits determined a significant rise time of the current in the source and explains the observed time of plasma heating and the rise time of the X-ray radiation intensity. It is shown that the parameters of the X-ray sources in the atmosphere of the AD Leo dwarf can be explained by assuming the simultaneous radiation of a large number of loops with electric currents which exceed by 1–3 orders of magnitude the electric currents in the coronal magnetic loops on the Sun. The latter fact can be related to the increased velocity of photospheric convection on the late-type stars compared with the Sun.

2. ELECTRIC CURRENT GENERATION IN THE MAGNETIC LOOPS

Convective flows of photospheric plasma, interacting with the magnetic field at the footpoint of a coronal magnetic loop, induce electric currents which are sources of free energy for plasma heating and charged-particle acceleration. This idea, whose origin goes back to [21, 22], is illustrated in Fig. 1 [23]. This figure shows a magnetic loop with the footpoints immersed into the photosphere and formed by the converging horizontal flows of photospheric substance. An indirect proof of the existence of strong electric currents in the coronal arches on the Sun is that the arch has an almost constant cross section throughout its entire length, which is unlikely for the potential magnetic field.

There are three important regions in the magnetic structure presented in Fig. 1 [24]. In region *1* located in the upper photosphere and the lower chromosphere, a magnetic field and the corresponding electric field are generated. Region *2* is located in the lower photosphere or directly under the photosphere. It is assumed that in this region the electric current I flowing through the magnetic loop is closed. The data on the electric fields distribution in the photosphere obtained using the magnetic field measurements [25] favor uncompensated electric currents. These data show that the electric current in the magnetic tube flows through the coronal part of the loop from one footpoint to another, and there are no reverse current manifestations. The current is closed in the subphotospheric region, where the conductivity becomes isotropic and the current flows along the shortest path from one footpoint of the loop to another. In region *3* (coronal

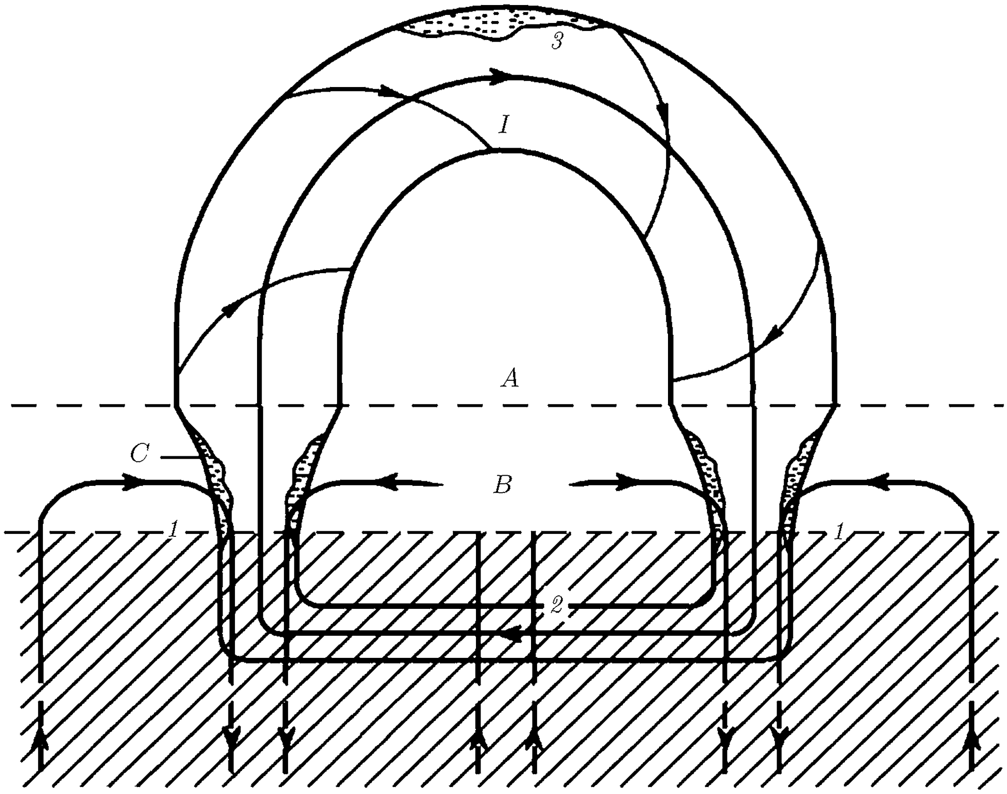

Fig. 1. Schematic representation of the coronal magnetic loop formed by the converging convective flows of photospheric plasma: *1* is the magnetic field generation region *2* is the electric field closure region, *3* is the coronal part of the loop; A is the chromosphere, B is the photosphere, and C is the the flute instability region.

part of the loop) the gas-kinetic pressure is smaller than the magnetic field pressure (the plasma parameter β is much less than unity) and the loop structure is force-free, i. e., the electric-current lines are directed almost along the magnetic field lines.

The above-considered magnetic loop with current is an equivalent electric circuit with inductance L and resistance R. This idea was formulated for the first time in [21] (circuit model of a flare). Slow current variations over a time much greater than the eigenoscillation period of the circuit are described by the equation [26]

$$\frac{L}{c^2}\frac{\mathrm{d}I}{\mathrm{d}t} + RI = \Xi, \tag{1}$$

where I is the total current flowing through the loop cross section along its axis,

$$R(I) = \frac{l_1}{\pi r_1 \sigma_1} + \frac{l_2}{\pi r_2 \sigma_2} + \frac{l_3}{\pi r_3 \sigma_3} + \frac{3\xi l_1 F_1^2 I^2}{\pi r_1^4 (2 - F_1) c^4 n_1 m_\mathrm{i} \nu'_{\mathrm{ia}1}} + \frac{3\xi l_3 F_3^2 I^2}{\pi r_3^4 (2 - F_3) c^4 n_3 m_\mathrm{i} \nu'_{\mathrm{ia}3}}, \tag{2}$$

l_1, l_2, and l_3 are the lengths of the parts of the electric circuit in the area of action of the photospheric electromotive force, in the region of closure of current under the photosphere, and in the corona, respectively (Fig. 1), r_1, r_2, and r_3 are the radii of the current channel, n_1, n_2, and n_3 are the plasma densities in the mentioned regions, σ_1, σ_2, and σ_3 are the corresponding isotropic conductivities,

$$\sigma_j = \frac{n_j e^2}{m_\mathrm{e}(\nu'_{\mathrm{ei}j} + \nu'_{\mathrm{ea}j})},$$

$j = 1, 2, 3$, the indices e, i, and a corresponds to the electrons, ions, and neutral atoms, respectively, e is the electron's charge, $\nu'_{klj} = [m_l/(m_k + m_l)]\nu_{klj}$ is the effective frequency of collisions between particles of types k and l with the masses m_k and m_l in the j region, respectively, ν_{klj} is the corresponding collision frequency, F_j is the relative density of neutrals, $\xi \approx 0.5$ is a form factor that arises during the magnetic loop volume integration, and c is the speed of light in free space. The dependence of the electric-current resistance is related to the contribution in the total resistance of the Cowling conductivity, which, in turn, depends on the self-consistent magnetic field of the loop. On the right-hand side of Eq. (1) is the electromotive force stipulated by the photospheric convection at the loop footpoint.

$$\Xi = \frac{l_1}{\pi c r_1^2} \int_0^{r_1} 2\pi V_r B_\varphi r \, \mathrm{d}r \approx \frac{|V_\mathrm{r}| \, I l_1}{c^2 r_1}, \tag{3}$$

where B_φ is the value of the azimuthal component of the magnetic field, $|V_\mathrm{r}|$ is the average value of the radial component of the convective flow velocity inside the loop in the area of action of the photospheric electromotive force. Estimates show that the terms in Eq. (2) related to the dynamo region of the loop, in which $F_1 \gg F_3$ and the radius r_1 of the current channel is much less than the corresponding coronal value r_3, give the main contribution to the circuit conductivity. This is due to a decrease in the ambient pressure with altitude. In this case, Eq. (1) takes the form

$$\frac{L}{c^2} \frac{\mathrm{d}I}{\mathrm{d}t} + aI^3 = bI, \tag{4}$$

where

$$a = \frac{3\xi l_1 F_1^2}{\pi r_1^4 (2 - F_1) c^4 n_1 m_\mathrm{i} \nu'_\mathrm{ia1}}, \qquad b = \frac{|V_\mathrm{r}| \, l_1}{c^2 r_1} - \frac{l_1}{\pi r_1^2 \sigma_1}. \tag{5}$$

For the initial condition $I(t = 0) = 0$ we obtain a solution to Eq. (4):

$$I(t) = (b/a)^{1/2} \, [1 - \exp(-2bc^2 t/L)]^{1/2}. \tag{6}$$

It follows from this formula that the current in the magnetic tube rises only under the condition $b > 0$, i. e., the current generation process in the region of photospheric electromotive force has a threshold in convection velocity. This condition means that the Reynolds magnetic number for the ionized plasma component should satisfy the condition $\mathrm{Re_M} = 4\pi \, |V_\mathrm{r}| \, r_1 \sigma_1 / c^2 > 4$. If the magnetic Reynolds number is large enough ($\mathrm{Re_M} \gg 1$), then the characteristic rise time of current in the equivalent electric circuit is equal to

$$\tau = \frac{L r_1}{2 \, |V_\mathrm{r}| \, l_1}. \tag{7}$$

This time can be long enough due to a high induction of the magnetic loops, which can explain a relatively long phase of Joulean plasma heating in the coronal part of the magnetic loops and a relatively slow rise in the soft X-ray radiation intensity. The steady-state electric current is determined by the formula

$$I_0 = \left[\frac{\pi \, |V_\mathrm{r}| \, r_1^3 n_1 m_\mathrm{i} \nu'_\mathrm{ia1} (2 - F_1)}{3\xi F_1^2} \right]^{1/2}. \tag{8}$$

Assume that in the area of action of the photospheric electromotive force the Joulean heating power is smaller than the optical radiation loss because of the high density of the substance. Therefore, there is no significant plasma heating or increase in the plasma ionization degree compared with the photospheric values. In this case, in Eq. (8) the relative density of neutral atoms can be assumed equal to unity ($F_1 \approx 1$). Conversely, in the coronal part of the loop, the relative density of neutral atoms is low ($F_3 \ll 1$); however, even a small number of neutrals is sufficient for switching of the effective current-dissipation channel related to the Cowling conductivity (the last term on the right-hand side of Eq. (2)). This is due to a decrease in the effective plasma conductivity

$$\sigma_3^{\mathrm{eff}} = \sigma_3 \bigg/ \left[1 + \frac{F_3^2 \omega_{\mathrm{e}} \omega_{\mathrm{i}}}{(2 - F_3)\nu'_{\mathrm{e}} \nu'_{\mathrm{ia3}}}\right], \tag{9}$$

where $\nu'_{\mathrm{e3}} = \nu'_{\mathrm{ei3}} + \nu'_{\mathrm{ea3}}$ since under the corona conditions the last term in the denominator of Eq. (9) is much greater than unity. In other words, a small number of neutrals may reduce dramatically the effective conductivity compared with the classical Spitzer conductivity, thereby increasing the current dissipation efficiency $q_{\mathrm{J}} = j^2/\sigma_3^{\mathrm{eff}}$, where j is the current density in the loop. In Eq. (9), ω_{e} and ω_{i} are the electron and ion gyrofrequencies, respectively.

3. HEATING OF THE CORONAL PART OF MAGNETIC LOOPS ON THE AD LEO DWARF

The electric current given by Eq. (8) corresponds to the current induced by photospheric convection in an individual magnetic loop. Assume that N_{L} magnetic loops contribute to the observed X-ray radiation of the red dwarf. In this case, it is needed to correct the magnetic loop parameters determined under the assumption $N_{\mathrm{L}} = 1$ [1]. If N_*, T_*, l_*, and r_* are the plasma density and temperature in the loops, the length, and radius of the loops, respectively, determined by the observed emission measure for the case $N_{\mathrm{L}} = 1$, then the true values of the parameters are correspondingly equal to [27]

$$n = n_*/N_{\mathrm{L}}^{1/8}, \qquad T = T_*/N_{\mathrm{L}}^{1/4}, \qquad l = l_*/N_{\mathrm{L}}^{1/4}, \qquad r = r_*/N_{\mathrm{L}}^{1/4}. \tag{10}$$

The case where several magnetic loops contribute to the flare radiation is typical of solar flares. For example, in the case of the Bastille, a well-known solar flare of July 14, 2000, an arcade of magnetic loop contained about 100 loops, with about 25 loops involved in the flaring process. Assume that plasma heating in the magnetic loops in the corona of the AD Leo dwarf is due to dissipation of the electric currents. We will determine the current in a separate loop required for heating the plasma up to the observed temperatures assuming that N_{L} magnetic loops contribute to the observed emission measure.

It was mentioned above that the last term on the right-hand side of Eq. (2), which is related to the presence of a small number of neutrals in the corona, gives the main contribution to the resistance of the coronal part of the loop. At temperatures significantly exceeding the ionization temperature of a hydrogen atom, and for an optically thin medium, the relative content of neutrals is determined by the formula [28, 29]

$$F \approx 0.15/T[K] \tag{11}$$

(hereafter the index 3 is omitted for simplicity). In this case, the effective number of ion — neutral atom collisions is equal to

$$\nu'_{\mathrm{ia}}[s^{-1}] \approx 10^{-11} F(n[\mathrm{cm}^{-3}] + n_{\mathrm{a}}[\mathrm{cm}^{-3}])\,(T[K])^{1/2} \approx 10^{-11} F n[\mathrm{cm}^{-3}](T[K])^{1/2} \tag{12}$$

($n_{\mathrm{a}} \ll n$), where n_{a} is the atom density. Allowing for Eqs. (2), (11), and (12), we find the Joulean dissipation rate of the current in a unit volume of the coronal part of the loop $q_{\mathrm{J}} = RI^2/(\pi r^2 l)$:

$$q_{\mathrm{J}}[\mathrm{erg}/(\mathrm{cm}^3 \cdot \mathrm{s})] = \frac{2.2 \cdot 10^{-9}(I[\mathrm{CGSunits}])^4}{(n[\mathrm{cm}^{-3}])^2 (r[\mathrm{cm}])^6 (T[K])^{3/2}}. \tag{13}$$

For the radiation loss function at temperatures $T \geq 2 \cdot 10^7$ K, we will use the formula [30]

$$q_{\mathrm{r}}[\mathrm{erg}/(\mathrm{cm}^3 \cdot \mathrm{s})] = 2.5 \cdot 10^{-27}(T[K])^{1/2}. \tag{14}$$

From the condition $q_{\mathrm{J}} = q_{\mathrm{r}}$, we estimate the electric current in a magnetic loop, at which the plasma is heated up to the X-ray temperatures,

$$I[\mathrm{CGSunits}] = 3.26 \cdot 10^{-5} n_*[\mathrm{cm}^{-3}](r_*[\mathrm{cm}])^{3/2}(T_*[K])^{1/2}/N_{\mathrm{L}}^{5/8}. \tag{15}$$

In Eq. (15), the asterisk denotes the magnetic loop parameters of the AD Leo dwarf, which were found assuming that one loop gives the total contribution to the observed emission measure of soft X-ray radiation, i. e., when $N_{\mathrm{L}} = 1$. It can easily be verified that the latter case requires very high currents in the coronal magnetic loop, at which the current-related azimuthal magnetic field exceeds considerably the atmospheric magnetic field $B_{\mathrm{ph}} \approx 4$ kG on the AD Leo dwarf. Assuming that $\bar{B}_\varphi = IN_{\mathrm{L}}^{1/4}/(cr_*) \leq 4 \cdot 10^3$ G, it can be found, e. g., for the observed parameters of the flare of March 1, 1993 [1] ($n_* \approx 10^{11}$ cm^{-3}, $r_* \approx 10^9$ cm, and $T_* \approx 2 \cdot 10^7$ K), an estimate for the minimum required number of magnetic loops involved in the flaring process: $N_{\mathrm{L}} \geq 35$. In this case, the current in a separate magnetic loop amounts to $I \leq 4.9 \cdot 10^{22}$ CGSunits $\approx 1.6 \cdot 10^{13}$ A, which is 2–3 orders of magnitude greater than the electric current in the magnetic loops on the Sun. Therefore, it is needed to answer the question on whether photospheric convection on the AD Leo dwarf can induce currents of the required value.

For this, one should know the electron and neutron-atom densities of the star. For red dwarfs with the radius $0.3R_\odot$, one can take a value of the order of $\rho \approx 5 \cdot 10^{-7}$ g/cm^3, which corresponds to the particle density $n + n_{\mathrm{a}} \approx n_{\mathrm{a}} \approx 3 \cdot 10^{17}$ cm^{-3}. The Saha formula at a photospheric temperature of 3400 K yields the electron number density $n \approx 3 \cdot 10^{10}$ cm^{-3}. Assuming that the magnetic flux tube has a radius $r_1 \approx 3 \cdot 10^7$ cm, which, in order of magnitude, is equal to the size of granules on the red dwarf [31], the required current generation imposes the following condition on the convection velocity:

$$V_{\mathrm{r}}[\mathrm{cm/s}] \approx 1.3 \cdot 10^8/N_{\mathrm{L}}^{5/4}. \tag{16}$$

Depending on the number of magnetic loops involved in the flaring process, the required velocity of photospheric convection can vary over a relatively wide range. For example, for the minimum number of loops $N_{\mathrm{L}} \geq 35$ the velocity should satisfy the condition $V_{\mathrm{r}} \leq 1.5 \cdot 10^6$ cm/s. For $N_{\mathrm{L}} \geq 100$, from Eq. (16) we obtain the estimate $V_{\mathrm{r}} \leq 4 \cdot 10^5$ cm/s. These values are about an order of magnitude greater than the photospheric convection velocity on the Sun, which obviously indicates that this process plays a more important role in the energy transfer on the red dwarfs compared with the Sun.

4. DISCUSSION

We have considered the possible reason for heating the plasma up to temperatures of about 10^7 K in the coronas of the stars belonging to the late spectral classes using the AD Leo red dwarf as an example. Assuming that the source of X-ray radiation is magnetic loops filled with hot plasma, the authors of [1] determined the magnetic loop parameters for 44 stars of spectral classes from F to M using the data on the emission measure and decay time in the soft X-ray range obtained onboard Extreme Ultraviolet Explorer. The results of the studies have shown that loops with a length of up to one-half of the star radius, a plasma temperature of 10^{11} to 10^{12} cm^{-3}, and a temperature of 10^7 to 10^8 K can exist on all stars of the mentioned types. From the data set presented there, we used the data on the magnetic loop parameters determined for 6 flares of soft X-ray radiation on the AD Leo dwarf on March 1, 1993, May 3, 1996, April 5, 1999, April 9, 1999, April 17, 1999, and May 9, 2000. We assumed that the plasma in the magnetic loops is heated as a result of dissipation of the electric currents induced by an electromotive force that arises during interaction between photospheric convection flows and the magnetic field at the magnetic loop footpoints. It should be mentioned that electric currents with a strength of 10^{10} to 10^{12} A are also observed in the magnetic loops on the Sun [25], and their origin is related to photospheric convection [24]. On the late-type stars, convection plays a more important role in the energy transfer from the star center to the star surface compared with the Sun; therefore, the existence of higher currents in the magnetic loops of the red dwarfs seems quite probable.

Assuming that a magnetic loop with current is an equivalent electric circuit with current-dependent resistance (Eq. (4)), we determined the induced electric current (Eq. (8)), as well as its characteristic rise time in the magnetic loop (Eq. (7)). This time is long enough ($\tau \approx 10^4$ s) due to a high inductance of the magnetic loops, which can explain a relatively long phase of Joulean plasma heating in the coronal part of the magnetic loops and a relatively slow rise of soft X-ray radiation from the AD Leo dwarf [20]. We determined the electric current (Eq. (15)) required for heating the plasma in the magnetic loops up to temperatures of about 10^7 K and showed that this current should be distributed over a fairly large ($N_{\mathrm{L}} > 35$) number of loops to ensure that the non-potential magnetic field related to this current does not exceed 4 kG on the star surface. Thus, a large number of magnetic loops should contribute to the observed emission measure of soft X-ray radiation on the AD Leo dwarf.

In the case of the solar corona, the emission measure of soft X-ray radiation flares is provided by the heating of one or several magnetic loops. This is related to the smaller observed emission measure for solar flares, as well as the smaller length and thickness of the loops, which requires smaller currents for heating to temperatures of about 10^7 K at the same initial temperature (see Eq. (15)). The maximum spottedness of the Sun does not exceed 0.5% of its surface, while on the red dwarfs it reaches tens of percent. This leads to more powerful flares on the red dwarfs compared with the solar flares. Obviously, significant differences in the power of the solar and stellar flares are due primarily to the differences in the areas encompassed by such processes, whereas the energy release from a unit surface is comparable in both cases [32].

We have shown that photospheric convection on the AD Leo dwarf can induce electric currents of the required value if the horizontal component of the photospheric convection velocity satisfies condition (16). Depending on the number of magnetic loops involved in the flaring process, the required velocity of photospheric convection can vary widely, from $V_{\mathrm{r}} \leq 1.5 \cdot 10^6$ cm/s for $N_{\mathrm{L}} \geq 35$ to $V_{\mathrm{r}} \leq 4 \cdot 10^5$ cm/s for $N_{\mathrm{L}} \geq 100$. We emphasize that these values are about an order of magnitude greater than the photospheric convection velocity on the Sun, which obviously indicates that this process plays a more important role in the energy transfer on the red dwarfs compared with the Sun.

That the number of loops involved in the flaring process on the AD Leo is relatively large makes corrections in the average length of magnetic loops (Eq. (10)): $\bar{l} \approx (0.5–0.6) \cdot 10^{10}$ cm, i. e., the ratio of the average length of the loop to the star radius is $\bar{l}/R_* \approx 0.2–0.25$, which is a factor of 2 to 3 less than the value obtained assuming that $N_{\mathrm{L}} = 1$ [1]. For the flaring magnetic loops on the Sun, the ratio of the loop length to the Sun's radius is usually 0.1–0.15, which is approximately two times less than a similar value for the AD Leo dwarf.

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