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LETTER

Letter to the Editor

Plasma heating in the solar corona by reconnecting current sheet

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Abstract. Flares of all scales, including nanoflares, are probably responsible for heating the solar corona. We propose a new model, describing in terms of self-similar solutions the process of plasma heating in the corona by thermal fluxes from high-temperature current sheets, where magnetic field lines are reconnected. The model demonstrates high efficiency of such a heating mechanism in the case of flares.

The differential emission measure of heated plasma is determined as a function of temperature. The spectral line intensities are calculated for ions Ca XIX, Fe XXV, and Fe XXVI. The pictures of radiative source (spatial distributions of the line intensities) are constructed. The results predicted by the model are discussed to compare with spectral and spatial observations of solar flares in soft X-rays.

Key words: Magnetohydrodynamics – Sun: corona – Sun: flares – Sun: magnetic fields

1. Introduction

The process of plasma heating in the solar corona is not well understood yet in spite of numerous speculations devoted to this problem and abundance of observational data. There is no doubt in the fact that magnetic fields can transport energy from the photosphere to the corona. However, the question is open whether dissipation of *waves or currents* is responsible for the transformation of the magnetic energy to the thermal and kinetic energy of hot, high-conductive plasma. Widely different positions have been taken in literature regarding the importance of these two processes (see, for a review, (Ulmschneider et al. 1991; Spicer & MacNeice 1992; Somov 1994)). Probably, both of them are equally important, but in this paper we consider only the second one, i.e. dissipation of currents, more exactly, dissipation of current sheets by magnetic reconnection in ordinary flares, microflares and nanoflares. This question was already studied by many authors (e.g. Forbes & Malherbe (1986), Parker (1988), Priest(1982)). However, our model distinguishes itself from ones earlier proposed, first, by suppositions and admissions of departure, and, second, by results, obtained mainly on the basis of the analytical simulation, namely: (a) the differential emission measure of heated plasma is determined as a function of temperature, (b) the spectral line intensities are calculated for ions Ca XIX, Fe XXV, and Fe XXVI, and (c) the spatial distributions of the line intensities are constructed. So far as the authors know, these are the first calculations of such kind.

Let us envision magnetic flux tubes being placed in the corona and interacting with a high-temperature current sheet (HTCS). First, they come into contact with the current sheet and penetrate into it. Then they reconnect and move with hot plasma inside the sheet to its edges (Fig.1). During this movement the plasma inside tubes is heated to the current sheet's temperature assumed to be as high as about 10^8 K. Second, having reached the edges, the magnetic flux tubes leave the sheet and continue the movement in the corona while disconnected from the source of energy. So, they gradually cool down, being hotter than the ambient plasma. The tubes of both kinds, disconnected and connected with the HTCS, heat the coronal plasma and lead to the emission of ions like the Ca XIX, Fe XXV, and Fe XXVI. The model of this process in the simplest approach is presented below.

2. Simulation Model and Results

Let us consider a single magnetic flux tube in the plane perpendicular to the electric current inside the HTCS. We suppose, for simplicity, that its cross-section area is constant. We also assume, in order not to obscure the essential physical point made in our paper, that all such tubes are straight and form the same angle θ with the current sheet's surface, so that $\text{tg}\,\theta \approx B_\perp/B_0 \approx 3\,10^{-3}$ is the relative value of the magnetic transverse component in the reconnecting current sheets (see Chapter 3 in (Somov 1992)). The typical time when the tube is inside the sheet is evaluated as $\tau \approx b/V \leqq 10^2$ s, where $b \leqq 10^9$ cm is the half-width of the sheet, $V \approx V_A \approx 10^7$ cm s^{-1} is the average velocity of

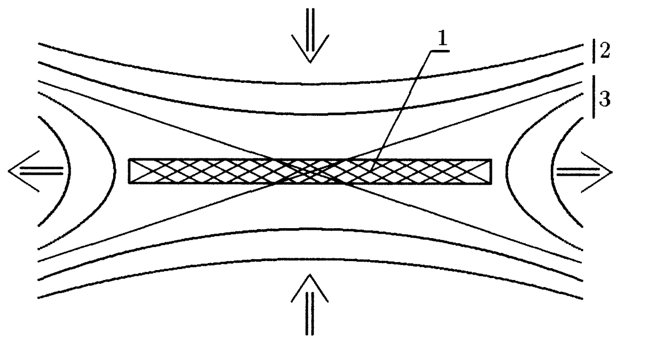

Fig. 1. The schematical picture of magnetic field lines inside and in the vicinity of the reconnecting current sheet:
1 – the current sheet, the direction of electric current "to us";
2 – magnetic tubes before the contact with the sheet;
3 – reconnected tubes.
The directions of plasma flow are shown by the double arrows.

the reconnected magnetic lines movement inside the sheet to its boundaries, V_A is the Alfvén velocity.

Obviously, the physical properties of the powerful heat wave propagating along the magnetic field tube are complicated because of its large amplitude and a number of kinetic processes such as electron-ion energy exchange, thermal escape of fast electrons, the effect of reversal current and so on (see Chapter 2 in (Somov 1992)). Strictly speaking, these properties could not be described by the model which takes into account only one sort of conductivity (classical or anomalous), ignoring fast hydrodynamic flows of emitting plasma (Somov et al. 1982), and the kinetic phenomena mentioned above. Nevertheless, it is just the model which is proposed below to evaluate the efficiency of the primary process (the corona heating by thermal fluxes from high–temperature reconnecting current sheets) and to determine specific observational features of this heating mechanism.

Two variants of mathematical problem have to be considered. First, during the time $0 \leqq t < \tau$, one edge of the magnetic tube is connected with the HTCS with temperature $T_s \approx 10^8$ K, but the other one is far from the HTCS and has the coronal temperature $T_0 \ll T_s$. Second, under the condition $t \geqq \tau$, the tube is not connected with the HTCS; therefore it does not receive heat from the sheet. Only redistribution of thermal energy by means of heat conduction occurs inside the tube.

In both cases the thermal conductivity equation is

$$\frac{\partial T}{\partial t} = a \frac{\partial}{\partial l}\left(T^{\alpha} \frac{\partial T}{\partial l}\right), \quad a = \frac{2\,æ_0}{3\, n_e\, k} = \mathrm{const}\,; \qquad (1)$$

(if there is no motion of the plasma introduced by the time depend temperature inhomogeneities). Here l is the coordinate being counted off from the HTCS along the tube; the thermal conductivity is described by the classical parallel electron coefficient $æ = æ_e^{\parallel} = æ_0 T^{\alpha}$, $\alpha = 5/2$; the electron concentration near HTCS is $n_e = \mathrm{const}$; k is the Boltsman constant.

Two similar problems were considered in (Zel'dovich & Raizer 1966). It follows the next solutions (for more details see (Oreshina & Somov 1995)).

First solution, for $0 \leqq t < \tau$,

$$\begin{cases} T(l) = T_s\, f(\xi), & 0 \leqq \xi \leqq \xi_0\,; \\ T(l) \equiv 0\,, & \xi \geqq \xi_0\,; \\ \xi = l\,(a\,T_s^{\,\alpha}\, t)^{-1/2} = 1.53\;10^{-5}\,\{\,n_e^{1/2}\, T_s^{-5/4}\,\}\, l\, t^{-1/2}\,. \end{cases} \qquad (2)$$

Here ξ is dimensionless self-similar variable, $\xi_0 \approx 0.963$, and the function $f(\xi)$ was determined numerically as a solution of an ordinary differential equation.

Second solution, for $t \geqq \tau$,

$$\begin{cases} T(l) = \left(\dfrac{Q^2}{a\,(t - t_0)}\right)^{1/(\alpha+2)} g(\eta) = \\ \quad = 1.96\; T_s\,(t - t_0)^{-2/9} \left[1 - \left(\dfrac{\eta}{\eta_0}\right)^2\right]^{2/5}, \\ \qquad 0 \leqq \eta \leqq \eta_0\,; \\ T(l) \equiv 0\,, \qquad \eta \geqq \eta_0\,; \\ \eta = l\,(a\,Q^{\alpha}\,(t - t_0))^{-1/(\alpha+2)} = \\ \quad = 3.51\;10^{-6}\,\{\,n_e^{1/2}\, T_s^{-5/4}\,\}\, l\,(t - t_0)^{-2/9}. \end{cases} \qquad (3)$$

where η is another undimensional coordinate, $\eta_0 \approx 1.01$;

$$g(\eta) = \left[\frac{\alpha}{2\,(\alpha + 2)}\;\eta_0^2\right]^{1/\alpha} \left[1 - \left(\frac{\eta}{\eta_0}\right)^2\right]^{1/\alpha}. \qquad (4)$$

The quantity Q is proportional to the entire thermal energy which has entered the magnetic tube from the HTCS; in our case it is determined from the solution of the first task (formulas (3)) at the moment $t = \tau$:

$$Q = \int_{-\infty}^{\infty} T_{(1)}(l, \tau)\,\mathrm{d}l \;=\; 2\,T_s\,(a\,T_s^{\alpha}\,\tau)^{1/2} \int_0^{\infty} f(\xi)\,\mathrm{d}\xi = \\ \;=\; 9.24\;10^5\,\{n_e^{-1/2}\, T_s^{9/4}\,\}. \qquad (5)$$

The detail results of computations are presented in (Oreshina & Somov 1995).

Then the temperature distributions calculated were integrated over all the magnetic tubes in the vicinity of the HTCS to find the differential emission measure

$$DEM(T) = \frac{\mathrm{d}}{\mathrm{d\,T}} \int n_e^2\;\mathrm{d}\,v \qquad (6)$$

for the whole X-ray source (v is its volume). This function is shown in Fig. 2. The corresponding value of the emission measure is

$$EM = \int n_e^2\;\mathrm{d}\,v \;=\; 1.13\;10^{49}\;\mathrm{cm}^{-3}\,. \qquad (7)$$

Here the following assumptions were taken: $n_e = 10^{10}\;\mathrm{cm}^{-3}$, $T_s = 10^{8}$ K, $L = 10^{10}$ cm is the length of the HTCS.

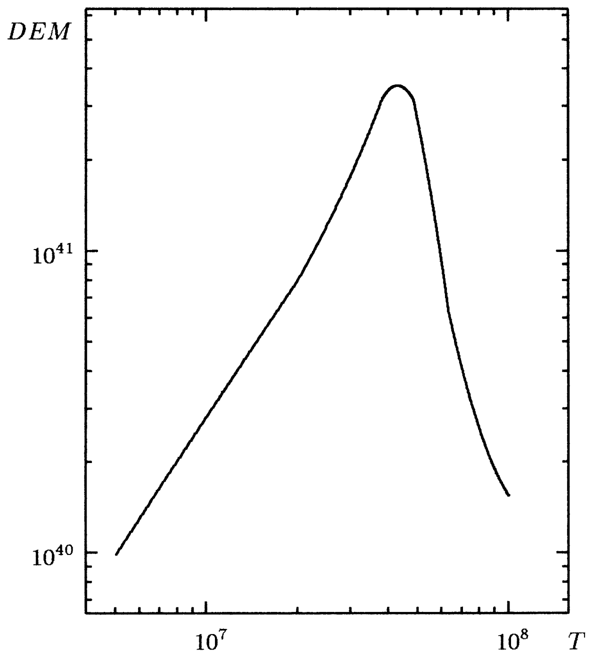

Fig. 2. The differential emission measure DEM (cm^{-3} K^{-1}) for the soft X-ray source as a function of temperature T (K)

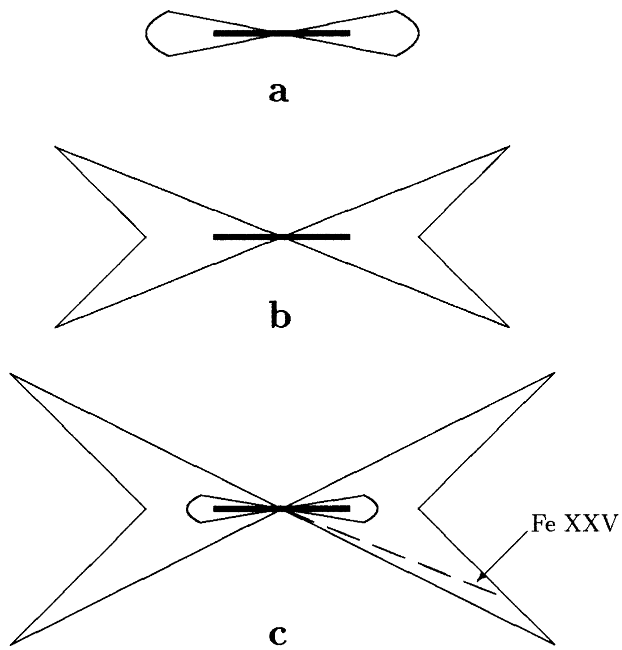

Fig. 3. The schematical (without keeping axial scales) distribution of intensity in the vicinity of the current sheet (shown as the horizontal solid bar) in the lines: **a** Fe XXVI (λ = 1.780 Å), **b** Fe XXV (λ = 1.850 Å), and **c** Ca XIX (λ = 3.173 Å)

Energy fluxes in the Ca XIX, Fe XXV, and Fe XXVI resonance lines were computed by using the known differential emission measure and the normalized power of soft X-ray lines (Mewe et al. 1985). That resulted in the following values for the resonance lines of ions:

Ca XIX (λ = 3.173 Å) $F_\lambda = 4.3\, 10^{-5}$ erg cm^{-2} s^{-1} ;
Fe XXV (λ = 1.850 Å) $F_\lambda = 9.4\, 10^{-4}$ erg cm^{-2} s^{-1} ;
Fe XXVI(λ = 1.780 Å) $F_\lambda = 1.6\, 10^{-4}$ erg cm^{-2} s^{-1} .

The spatial distributions of the same line intensities in the vicinity of the current sheet were plotted in Fig. 3 without keeping axial scales. As one can see, the Fe XXVI emission concentrates near the current sheet, while the Ca XIX occurs at a distance from it.

3. Discussions

The model of plasma heating in the solar corona by thermal fluxes from the high-temperature current sheet, presented above, is the first, quite rough approximation to a real situation. The advantage of this approach consists in the possibility to obtain the relatively simple initial equations and to find their semi-analytical solutions for the heat waves propogating along magnetic tubes.

The model may be used as a basis to construct more complicated models which will include such effects as electron-ion energy exchange, thermal escape of fast electrons, hydrodynamic flows of emitting plasma and so on. The comparison of future results with ones presented in our paper will give the possibility to estimate more accurately the influence of all the factors on considered process.

It is clear that the model neglects all the effects which could reduce X-ray emission of plasma heated by the current sheet. In this context the obtained results (the differential emission measure as a function of temperature, the soft X-ray line intensities) should be considered only as the upper limits on corresponding quantities. The values predicted by the model exceed the observed ones indeed.

In relation to the predicted spatial distributions of soft X-ray line intensities, comparison of them with ovserved by the *Yohkoh* soft X-ray telescope (SXT) would be greatly interesting and it requires more detailed study of X-ray images from a quantitative point of view. On a qualitative level one can speculate only about the similarity between calculated intensity distributions and the angular (cusp) features observed in flares and in active regions (e.g., Ichimoto et al. 1992; Tsuneta et al. 1992).

It is also necessary to emphasize that the results (in particular, DEM(T)) are sensitive to the input parameters of the model (especially, the current sheet temperature T_s and the electron density of the ambient plasma n_e). Therefore the main conclusion which may be done on the basis of the results represented here consists in the following. Soft and hard X-ray observations will be an effective tool for diagnostic and investigations of reconnecting current sheets in the solar corona.

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