MODEL OF MOTION OF THE X-RAY LOOP-TOP SOURCE AT THE BEGINNING OF CUSP-TYPE FLARES

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Abstract. A model with a 1-D collapsing magnetic trap is proposed for an explanation of the motion of the X-ray loop-top source at the beginning of cusp-type flares. Considering plasma heating due to the betatron mechanism an analytic formula for the temporal and spatial evolution of heated plasma temperature in the trap is derived. Using the formula and the relation for thermal bremsstrahlung flux, the time evolution of the X-ray intensity profile in the trap is computed numerically. The model explains not only the downward motion of the X-ray loop-top source observed at the beginning of cusp-type flares, but also the upward motion which follows.

Key words: solar flares - heating processes - X-ray emission

1. Introduction

There are new RHESSI observations of flares with cusp topology showing that the X-ray loop-top sources move firstly downwards and then, after their motion stops, upwards (Sui and Holman 2003, Liu et al. 2004, Sui et al. 2004). While the latter phase is known for a long time and explained as a successive loop formation (Švestka et al. 1987, Tsuneta et al. 1992, Gallagher et al. 2002), the explanation of the early phase with the downward motion remains unclear. Furthermore, Sui et al. (2004) have found that the X-ray loop-top sources observed at higher energies are located above the X-ray loop-top sources observed at lower energies and show systematically higher downward velocities.
Karlický and Kosugi (2004) have recently studied the betatron acceleration and heating processes in the collapsing magnetic trap formed in the cusp-flare topology. They found that for a sufficiently fast collapse of the trap and sufficiently high energies of the injected electrons, overcoming the collisional losses, the electrons can be accelerated by this secondary acceleration process to very high energies. The computations showed that the high-energy electrons are accumulated in the central part of the collapsing magnetic trap due to the increase of their pitch angles. This effect explains the formation of the loop-top sources observed in hard X-ray and radio emissions (Masuda et al. 1996, Nakajima and Yokoyama 2002) in a very natural way. Because the processes in the collapsing trap not only accelerate the superthermal particles but also they heat the thermal ones, the super-hot loop-top sources (Tsuneta et al. 1997) can be explained in the same way.

In the present paper, using the collapsing magnetic trap model (Karlický and Kosugi 2004), we try to explain the above mentioned downward motion of the X-ray loop-top source observed at the beginning of cusp-type flares.

2. Model

In the cusp topology of flares the plasma flowing from the reconnection site moves downwards together with magnetic field lines (Figure 1). In the region of increasing magnetic field strength the plasma is adiabatically heated by the betatron mechanism. The process is most efficient in the central part of the collapsing trap structure, i.e. along the vertical axis of the cusp, where consequently the X-ray source is formed. Therefore, in this study, we consider only the processes along the vertical axis of the cusp structure, i.e. a 1-dimensional collapsing trap in the region between the reconnection site and the top of the growing flare loop system.

Plasma flowing from the reconnection site stops at a certain point in the flare atmosphere due to the tension of magnetic field in the flare loops. For the same reason further magnetic field lines and plasma entering this region stop in a higher position relative to the previous. Therefore, the bottom of the collapsing trap has to move upwards due to the successive loop formation (e.g. Švestka et al. 1987).

Assuming, for simplicity, a stationary state of successive flare loops formation under the trap, i.e. a constant upward velocity of the collapsing
Figure 1: Scheme of the 1-D collapsing magnetic trap model with the X-ray loop-top source located in the cusp topology of the flare. Due to the successive loop formation under the trap, the trap moves upwards with the velocity $v_{\text{up}}$.

trap bottom $v_{\text{up}}$, also the upper part of the cusp structure can be assumed to be in a stationary state.

Now, let us consider the processes in the collapsing trap in a coordinate system co-moving with the trap, with the origin $h_T = 0$ located at the bottom of the trap. In the stationary regime the flow of the magnetic flux in the collapsing trap has to be conserved:

$$Bv = C,$$  \hspace{1cm} (1)

where $B$ is the magnetic field, $v$ is the plasma velocity, and $C$ is a constant. The velocity of plasma outflowing from the reconnection site and entering the collapsing trap at its top, near the reconnection site, corresponds to the Alfvén speed in the plasma inflow region (Priest 1982). The plasma velocity decreases with decreasing height in the trap and the decrease is accompanied with a growth of the magnetic field strength (Equation (1)). To fit the plasma velocity at the bottom of the collapsing trap with the fact that plasma is stopped here (in respect to the solar atmosphere – plasma is confined in the flare loops which are in rest to the atmosphere), we put the plasma velocity at the bottom of the collapsing trap $v_{\text{bot}} = -v_{\text{up}}$ (in respect to the trap coordinate system). By this relation the process of a successive loop formation under the collapsing trap is included into the model.

Considering that the Alfvén speed in the corona is much higher ($\sim 10^3$ km s$^{-1}$) than the growth-velocity of the flare loop system ($\sim 20$ km s$^{-1}$),
the total compression ratio in the whole collapsing trap is relatively high
\( v_{\text{top}}/v_{\text{bot}} = B_{\text{bot}}/B_{\text{top}} \sim 50 \), where \( v_{\text{top}}, B_{\text{top}}, v_{\text{bot}} \) and \( B_{\text{bot}} \) are the plasma velocities and the magnetic fields at the top and bottom of the collapsing trap.

Now, let us specify the magnetic field and plasma velocity structure of the collapsing trap. In a stationary regime of the trap collapse, we define a time parameter \( t_h \), which expresses the time needed by a plasma element, associated with a magnetic field line, to cover the distance between the trap top and a specific height in the trap \( h_T \). Using the time parameter \( t_h \), we prescribe the magnetic field in the trap as

\[
B(t_h) = B_{\text{top}} \exp(t_h/\tau_{tc}) \tag{2}
\]

where \( \tau_{tc} \) is the characteristic time of the trap collapse. Combining Equations (1) and (2), we get an expression for the plasma velocity in the collapsing trap

\[
v(t_h) = v_{\text{top}} \exp(-t_h/\tau_{tc}) \tag{3}
\]

and from this equation also the time needed by a plasma element to cover the distance between the top and bottom of the collapsing trap

\[
t_{h_{\text{bot}}} = -\tau_{tc} \ln \left( \frac{v_{\text{bot}}}{v_{\text{top}}} \right) \tag{4}
\]

The position of a specific plasma element at a time \( t_h \) can be now obtained by integrating Equation (3) and putting \( h_T = 0 \) at the bottom of the trap

\[
h_T(t_h) = \left| v_{\text{top}} \right| \tau_{tc} \left[ \exp(-t_h/\tau_{tc}) - \exp(-t_{h_{\text{bot}}} / \tau_{tc}) \right]. \tag{5}
\]

Combining Equations (3) and (5), the relation between the height and velocity of plasma in the trap in a stationary regime is

\[
h_T(v) = \left( |v| - |v_{\text{bot}}| \right) \tau_{tc}. \tag{6}
\]

Knowing the height of a plasma element in the coordinate system co-moving with the trap, we can compute its height \( h_A \) in respect to the coordinate system in rest to the solar atmosphere as

\[
h_A(t) = h_T + v_{\text{bot}} t + h_A^0, \tag{7}
\]
where $h_0^t$ is the height of the bottom of the collapsing trap at the time $t = 0$ in the coordinate system fixed in the solar atmosphere.

Concerning the density in the trap, we use the same parametric dependence as for the magnetic field

$$n(t_h) = n_{top} \exp(t_h/\tau_{tc}),$$

where $n_{top}$ is the plasma density at the top of the trap. From Equations (3) and (8) it follows that the mass flow $nv$ in the collapsing trap is conserved.

Knowing the magnetic field and density structure of the trap, we compute the evolution of plasma temperature in the trap by solving the following equation (Eq. (12) in Karlický and Kosugi 2004) and by specifying the plasma temperature at the injection point located at the trap top $T_{top}$ at the initial time

$$\frac{1}{T_{top}} \frac{dT}{dt} = \frac{2}{3} \frac{1}{B_{top}} \frac{dB}{dt} + H - Q. \quad (9)$$

Here $H$ stands for an additional heating, and $Q$ for the energy losses (radiative and conductive). Equation (9) can be solved either numerically or by assuming $H - Q = 0$ and the magnetic field according to Equation (2) analytically. In the latter case the temperature in the trap is

$$T(t_h) = \frac{2}{3} T_{top} \exp(t_h/\tau_{tc}) + \frac{1}{3} T_{top}, \quad (10)$$

where $T_{top} = const$. This temperature profile corresponds to a fully developed stationary regime of the collapsing trap. The temperature reaches its maximum at the bottom of the trap, which in the coordinate system fixed in the solar atmosphere moves upwards with the velocity $v_{up}$.

But at the beginning of flares the situation is different. The system is not immediately in a fully developed stationary regime, but it gradually evolves into it. To take the evolution at the beginning of flares into account we assume time variations of the temperature of plasma injected into the trap (i.e. $T_{top} = T_{top}(t)$), whereas the magnetic field and plasma velocities in the trap are assumed to be the same as in the stationary regime. Now the temperature in the collapsing trap can be expressed as

$$T(h_T, t) = \frac{2}{3} T_{top}(t - t_h) \exp(t_h/\tau_{tc}) + \frac{1}{3} T_{top}(t - t_h), \quad (11)$$

where $T_{top}(t-t_h)$ means the temperature at the top of the trap at the time $t-t_h$ and the relation between $h_T$ and $t_h$ is given by Equation (5).

Now, using the formula for the thermal bremsstrahlung flux (Tandberg-Hanssen and Emslie 1988)

$$I(E_x) = D \frac{n^2 V}{E_x T^{1/2}} \exp \left(-\frac{E_x}{kT}\right),$$  \hspace{1cm} (12)

where $D$ is a constant, $E_x$ is the radiation energy, $T$ and $n$ are the plasma temperature and density, $V$ is the source volume, and $k$ is the Boltzmann constant, the thermal X-ray emission along the 1-D trap (Figure 1) can be computed.

3. Results

The presented model explains the downward velocities of X-ray sources at the beginning of flares in the context of downward plasma velocity in
the collapsing trap. Observed velocities of the X-ray loop-top sources are relatively low (|\(v_s\)| < 50 km s\(^{-1}\)). Because such plasma velocities occur only in the bottom part of the collapsing trap, in the following we will focus our attention only to this part of the trap. Moreover, the characteristic time in the bottom part of the collapsing trap can be much longer than in the upper part, especially at the beginning of flares, when the system of magnetic field lines in the bottom part of the collapsing trap is compressed and it evolves to a fully stationary regime. Note that a decrease of the spatial extent of the trap corresponds to the shortening of the characteristic time. In the following calculations we take the characteristic time \(\tau_{tc} = 100\) s.

The height extent of the bottom part of the collapsing trap is defined by the values of plasma velocities at the top and bottom boundaries of the bottom part of the collapsing trap. For example, the velocities \(4 \times v_{bot}\) (in
the following it is designated as \( v_{\text{top}} \) – the velocity at the top of the bottom part of the trap) and \( v_{\text{bot}} \) (the velocity at the bottom of the trap), for \( v_{\text{bot}} = -v_{\text{up}} = 20 \text{ km s}^{-1} \), give the height extent of the bottom part of the trap 6 Mm (constant in time). Furthermore, we assume the magnitude of the magnetic field strength and plasma density at the bottom of the collapsing trap – the stop position of the downward moving plasma in the solar atmosphere as \( B_{\text{bot}} = 200 \text{ G} \) and \( n_{\text{bot}} = 2 \times 10^{11} \text{ cm}^{-3} \). Thus for \( v_{\text{top}}/v_{\text{bot}} = 4 \), at the top boundary of the bottom part of the collapsing trap the magnetic field and density is 50 G and \( 5 \times 10^{10} \text{ cm}^{-3} \), respectively.

In the initial state the temperature in the trap is assumed to be constant everywhere \( T = 10^6 \text{ K} \) (except the trap top, see the following). Then at the top boundary of the bottom part of the trap a growing temperature of the injected plasma in the time interval \( 0 - 30 \text{ s} \) is assumed. The growth of the injected plasma temperature can be attributed to the preheating in the reconnection site and in the upper part of the collapsing trap. After the initial 30 s the temperature of the injected plasma is assumed to remain constant, i.e.

\[
T_{\text{top}}(t) = 1.5 \times 10^7 + 1.66 \times 10^5 t \quad \text{K}, \quad \text{for} \quad t \equiv (0, 30) \text{ s},
\]

\[
T_{\text{top}}(t) = 2 \times 10^7 \text{ K} \quad \text{for} \quad t \geq 30 \text{ s}.
\]

For such high temperatures the adiabatic heating is much greater than radiative losses. Using Equation (11) we computed the time and spatial evolution of the temperature profile in the trap. Knowing the time evolution of the temperature profile in the trap we computed the X-ray intensity profiles in the bottom part of the trap. The results for times 70, 85, and 130 s after the onset of preheated plasma injection are shown in Figure 2. The intensity maxima in both energies (6 keV – full lines, 12 keV – dotted lines) move downwards towards the trap bottom, where the plasma temperature reaches its maximum. Then the plasma flow crosses the bottom boundary of the trap and is stopped relative to the solar atmosphere. As the heating due to the betatron mechanism stops, the plasma starts to cool. Although the cooling processes under the trap are not considered here we only assume a decrease of plasma temperature under the trap so the temperature maximum remains at the bottom of the trap, which moves upwards in the coordinate system fixed in the solar atmosphere.

The positions and velocities of the X-ray maxima for 6 keV and 12 keV in the solar atmosphere are shown in Figure 3. It can be seen that
due to the superposition of the X-ray source velocity inside the trap and the upward motion of the whole trap, the downward motion of the X-ray sources eventually turns into an upward motion. Figure 3 shows that at higher photon energies (12 keV) the X-ray source is located above those at lower energies (6 keV) and has higher downward velocities which is in good agreement with the observational findings of Sui et al. (2004).

4. Conclusions

Considering a simple model with preheated plasma injected into the bottom part of a moving collapsing magnetic trap we are able to explain the observed characteristics of the X-ray flare loop-top sources. In the collapsing trap, plasma moves towards the bottom of the trap and during the motion it is heated by the betatron mechanism. At the same time the intensity maxima of the X-ray loop-top sources move downwards and the X-ray source emitting at 12 keV is located above the source emitting at 6 keV. This can be attributed to the temperature profile of the plasma flow that can be modified by injected plasma temperature variations. Due to the plasma velocity pattern in the collapsing trap the X-ray loop-top source emitting at higher energies moves downwards faster than the source emitting at lower energies. When the heated plasma reaches the collapse trap bottom, its motion (relative to the solar atmosphere) and heating stops, the plasma leaves the trap and starts to cool. The temperature maximum thus remains at the collapse trap bottom, which in the coordinate system fixed in the solar atmosphere moves upwards. The intensity maximum of the X-ray source follows the temperature maximum, i.e. it moves also upwards.

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References

MODEL GIBANJA IZVORA X-ZRAKA NA VRHU PETLJE ZA POČETKA DVOVLAKNASTIH BLJESKOVA

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Izlaganje sa znanstvenog skupa

Sažetak. Predlaže se 1-D model urušavajuće magnetske zamke za objašnjenje gibanja izvora X-zraka na vrhu petlje tijekom početka dvovlaknastih bljeskova. Uz pretpostavku zagrijavanja plazme uslijed betatronskog mehanizma izvodi se analitička formula za vremenski i prostorni razvoj temperature zagrijavane plazme u zamci. Koristeći tu formulu i relaciju za tok termičkog zakoćnog zračenja numerički se izračunava vremenski razvoj profila intenziteta X-zraka u zamci. Model objašnjava ne samo silazno gibanje izvora X-zraka na vrhu petlje opažano za početka dvovlaknastih bljeskova, već i uzlazno gibanje koje potom slijedi.

Ključne riječi: Sunčevi bljeskovi - procesi zagrijavanja - emisija u X-zrakama