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Collapsing magnetic trap as accelerator of electrons in solar flares

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Abstract

A collapsing trap in the cusp topology of solar flares is simulated using a 2D MHD model. Then in this collapsing trap trajectories of test electrons and their acceleration are studied in detail. In the model we use the test particle technique with the guiding centre approximation including also collisional losses and scattering of test electrons. Computing the X-ray emission of the accelerated electrons it is shown that the acceleration process in the collapsing trap easily explains the formation of observed loop-top X-ray sources.

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Keywords: Solar flares; Particle acceleration; X-ray emission

1. Introduction

It is commonly accepted that in solar flares electrons are accelerated in two steps: (1) in the DC electric field of the magnetic reconnection (Litvinenko, 1996), which is considered as a primary acceleration process, and (2) in secondary acceleration processes: e.g. (a) an acceleration in the MHD turbulence generated in plasma reconnection outflows (LaRosa and Moore, 1993; Miller et al., 1996), (b) the shock-drift (Holman and Pesses, 1983) and (c) diffusive shock accelerations (Cargill et al., 1988), and (d) the Fermi acceleration in termination shock (Tsuneta and Naito, 1998).

Studying processes in the flare cusp-structure, Somov and Kosugi (1997) recognized here a system of moving magnetic field lines and flowing plasma where the magnetic field changes in time. This system was called the collapsing magnetic trap and proposed as an efficient accelerator of particles. Karlický and Kosugi (2004) studied this acceleration process numerically in a simplified form of the collapsing trap. They showed an importance of this acceleration process for an explanation of loop-top X-ray sources (Masuda et al., 1996).

In this contribution, starting from a simulated collapsing trap in the MHD model the acceleration of electrons is studied by the test particle technique. The X-ray emission of these accelerated electrons relevant to observations is computed.

2. Simulations

First, we simulated the flare cusp-structure with the collapsing trap. We started with a symmetric vertical Harris-type current sheet located in the middle of the 2D rectangular computation domain. This current sheet, in a small surrounding of the origin (see Fig. 1), was perturbed by an anomalous resistivity for a short time. The system evolved according to the MHD equations which are solved using the 2D modified Lax–Wendroff scheme. The free boundary conditions on the upper boundary and the left and right sides were considered. The symmetric and anti-symmetric relations were used for plasma density and magnetic field and velocity components at the bottom boundary. Furthermore, after an initiation of the cusp-structure the parameters at the bottom boundary were

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fixed simulating thus an effect of dense plasma of the solar photosphere. The anomalous resistivity was computed dynamically when the electric current density at some location exceeded a given threshold. For more details, see Karlický and Bárta (2006).

Computations were made in dimensionless variables and then the results were scaled to those appropriate for solar flares. For the scaling we used for the magnetic field $B_0 = 100$ G, for the plasma density $n_0 = 10^{10}$ cm^{-3} and for the spatial grid distance 100 km (in the MHD model the grid distance is $\Delta x = 0.045\ L_A$), where L_A is the current sheet width.

Thus, the cusp flare structure with the collapsing trap was simulated. Its magnetic field, plasma density, and velocity are shown in Figs. 1 and 2. As seen here, the collapsing trap (the downward moving plasma with the magnetic field lines) is located at the positions $y \approx 20$–35 Mm under the current sheet. But, it is not a simple trap as usually assumed, this trap consists of the structure with the return current at the position $y \sim 30.5$ Mm (the bumps in the magnetic field, velocity, and density profiles – Fig. 2; compared with the similar structure computed by Magara et al. (1996) (Plate 26)). This structure at first sight reminds to the standing fast-mode MHD 'termination' shock which is expected to occur at the location where the supersonic reconnection outflow meats the flare loop system (e.g. Aurass et al., 2002). However, it should be noted that the behavior of the plasma parameters, shown in Fig. 2, is not consistent with the perpendicular fast-mode MHD shock.

In our model the electric field has only the component perpendicular to the MHD computational plane, i.e. perpendicular to the magnetic field. In this case the guiding center's motion of test electrons occurs mainly in this MHD computational plane ($x - y$). As shown by Giuliani et al. (2005) besides this main motion there is a small

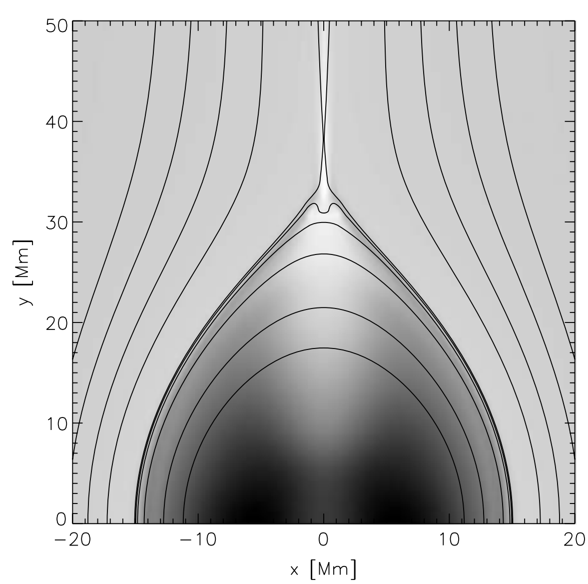

Fig. 1. The computed cusp magnetic field structure with the collapsing trap. The contours are magnetic field lines and the grey colours express the plasma density; dark means dense parts.

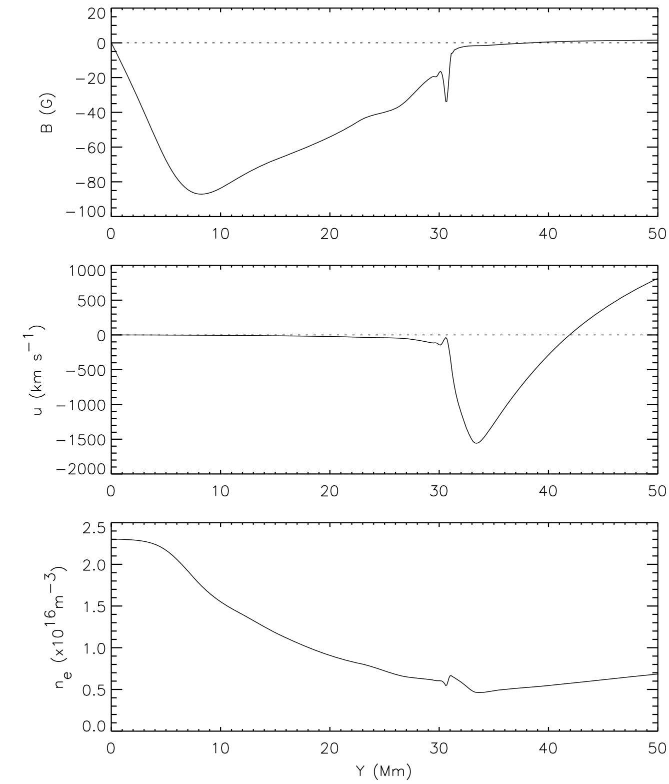

Fig. 2. The magnetic field (the solid line means B_x and the dotted line B_y), plasma velocity (the solid line means u_y and the dotted line u_x) and density profiles along the vertical axis of the collapsing trap.

additional (curvature) drift in the invariant z-direction which plays an important role in the electron acceleration. Namely, this drift is in the electric field direction. Therefore, in our model for the test electron motion and acceleration we use the equations as follows (Northrop, 1963; Giuliani et al., 2005):

$$\frac{d\boldsymbol{R}}{dt} = \boldsymbol{u}_\perp + v_\parallel \boldsymbol{b}, \tag{1}$$

$$\frac{d(\mu B)}{dt} = \frac{\partial(\mu B)}{\partial t} + v_\parallel \frac{\partial(\mu B)}{\partial s} + \boldsymbol{u}_\perp \cdot \nabla(\mu B), \tag{2}$$

$$\frac{d}{dt}\left(\frac{m_e}{2} v_\parallel^2\right) = m_e v_\parallel^2 \frac{\boldsymbol{E} \times \boldsymbol{b}}{B} \frac{\partial \boldsymbol{b}}{\partial s} - v_\parallel \frac{\partial(\mu B)}{\partial s}, \tag{3}$$

where $\boldsymbol{E} \equiv (0, 0, E_z)$ is the electric field, $\boldsymbol{b} = \boldsymbol{B}/B$ is the unit vector in the magnetic field direction, $\boldsymbol{u}_\perp$ is the plasma velocity perpendicular to the magnetic field $\boldsymbol{B} \equiv \boldsymbol{B}(\boldsymbol{R},t)$ computed in the above mentioned MHD model, $v_\parallel$ is the electron velocity parallel to the magnetic field, μ is the magnetic moment, $\boldsymbol{R}$ is the vector location of the guiding centre, m_e is the electron mass, and s is the coordinate along the magnetic field line. The term $\mu\boldsymbol{B}$ is the electron energy perpendicular to the magnetic field, and $v_\parallel \partial(\mu\boldsymbol{B})/\partial s$ is the mirror term, which appears with opposite signs in the energetic equations (2) and (3). The first term on the right-hand side of Eq. (3) expresses the electron energy gain due to the curvature drift.

Furthermore, in each time step we computed the energy losses and pitch angle scattering of electrons due to