The numerical MHD simulation of solar flares

A.I. Podgorny\textsuperscript{a,*}, I.M. Podgorny\textsuperscript{b}, N.S. Meshalkin\textsuperscript{c}

\textsuperscript{a}Lebedev Physical Institute RAS, Leninsky Prospect, 53, Moscow 119991, Russia
\textsuperscript{b}Institute for Astronomy RAS, Pyatnitskaya Street, 48, Moscow 119017, Russia
\textsuperscript{c}Institute for Solar-Terrestrial Physics SO RAS, Lermontov Street, 126a, Irkutsk 664033, Russia

Accepted 27 August 2007
Available online 5 October 2007

Abstract

The 3D MHD calculations carried out above the active region AR 0365 before the flare on May 27, 2003 show solar flare energy accumulation with current sheet (CS) creation in the singular line (SL) vicinity. The maximal radio-emission intensity measured with the SSRT radio telescope (Irkutsk) coincides with the current density maximum in CS. The obtained results confirm the solar flare electrodynamical model and open the possibility for improving the solar flare prognosis.

r 2007 Elsevier Ltd. All rights reserved.

Keywords: Solar flare; Current sheet; Radio-emission; MHD

1. Introduction

The flare electrodynamical model (Fig. 1) is based on the numerical 3D MHD simulation of energy accumulation in the current sheet (CS) magnetic field (Podgorny and Podgorny, 1992, 2001, 2006). The model explains phenomena observed during a flare including visible ribbons, X-ray radiation, coronal mass ejection, and spectra of solar flare cosmic rays (Podgorny and Podgorny, 2006).

It has been shown in the MHD numerical experiments that CS forms (Podgorny and Podgorny, 1992) before the onset of the flare in the corona in the magnetic singular line (SL) vicinity as a result of focusing of disturbances coming from the photosphere—in particular, new magnetic flux, whose direction is opposite to that of the old flux of the active region emerges (Podgorny and Podgorny, 2001). CS is stable for a long period, and energy is stored in its magnetic field, then it rapidly realized during the solar flare when CS transforms into an unstable state. CS is highly stable during its formation due to the presence of a normal magnetic field component in CS and the plasma flow along the sheet. This stage is followed by quasi-stationary evolution of CS, during which the total mass of the plasma in CS decreases due to the ejection of plasma accelerated by the magnetic tension from CS. The plasma density is reduced, so that the plasma density remains virtually constant at the center of CS and decreases near its boundary.

The basic dissipation mechanism during the explosive decay is reconnection, which results in plasma heating in the vicinity of SL. Depending on the initial condition of the field in the active region...
and the character of photospheric disturbances in
the preflare state, CS can be inclined to the solar
surface at various angles. The solar flare model for
the vertical CS is shown in Fig. 1. In that case the
solar flare and CME develop simultaneously in the
same explosive event. The plasma flows into CS
from both sides with the velocity \( V_{\text{in}} \) together with
frozen-in magnetic field lines spreading along the
CS upward and downward during field line recon-
nection. The \( \frac{j \times B}{c} \) force accelerates the plasma,
and the upward plasma stream ejects the solar
material into space—coronal mass ejection devel-
ops. The plasma accelerated downward, with
shrinking magnetic lines, forms a postflare loop.

An important property of CS is the Hall electric
field \( E_h = \frac{j \times B}{n \, c} \) generation inside the sheet,
whose direction coincides with the plasma velocity
along CS. Since the plasma conductivity in the
magnetic field is highly anisotropic, the Hall electric
field generates electric currents along the magnetic
lines intersecting CS. The field-aligned currents are
shown by bold lines in Fig. 1. These field-aligned
currents are closed inside the photosphere due to the
presence of neutral atoms there. The electrons
accelerated in the upward field-aligned current precipitate onto the chromosphere, giving rise to
the glow of flare ribbons and hard X-ray emission.
Typically, the energies can reach several hundred
keV. The electrons heat the chromosphere and produce chromosphere evaporation filling the loop
by plasma.

The primary flare energy release in the corona has
been confirmed by measurements of hard X-ray
emission (Tsuneta et al., 1997; Lin et al., 2003). The
coronal X-ray source with the temperature of
\( \sim 3 \) keV has been observed in RHESSI (Lin et al.,
2003) measurements above the arch. The photos-
pheric X-ray sources produced by electron beams
with energy up to \( \sim 100 \) keV are located in the
magnetic arch footpoints. Apparently, these elec-
trons gain their energy accelerating along field-
aligned currents.

Several models of CME and solar flares creation
are based on twisted flux rope ejection (Lin, 2004;
Forbes, 1991; Mikic et al., 1988; Amari et al., 2000;
Roussev et al., 2004; Kliem et al., 2004). The plasma
acceleration can be described as rope current interaction with the image current situated under
the photosphere. If the rope current \( I \) is directed
perpendicular to the arch magnetic field \( B_{\text{ar}} \) of an
active region, the force \( \frac{I \times B_{\text{ar}}}{c} \) also appears that
can supply additional acceleration or deceleration
of the rope. In the point, where these forces are
equal and oppositely directed (upward and down-
ward), the unstable equilibrium takes place. Such a
situation is considered by Lin (2004), Forbes (1991),
and Mikic et al. (1988). The rope accelerated
upward stretches magnetic field into configuration
of CS, where magnetic energy is effectively accu-
mulated for a solar flare, and the ejected rope
produces CME.

The most difficult problem of such models is the
explanation, how such a rope can be created. In the
works of Lin (2004) and Mikic et al. (1988) it is
supposed, that the rope exists from the very
beginning. Amari et al. (2000) and Roussev et al.
(2004) attempt to obtain the rope creation in the
corona by twisting of foot-points of the arches and
by shear-type foot-point motion on the photo-
sphere. In the unstable equilibrium a rope should be
created in very short time before the ejection. The
rope appearance can be also explained by its
emergency from-under the photosphere. Such an
emergence has to create tremendous photospheric
disturbances before the flare. The interesting me-
chanism of flare and CME is proposed by Kliem
et al. (2004). The rope becomes unstable due to the
kink instability at critical magnetic lines twisting,
and, as a result, rope is ejected.

The interesting results have been obtained by
simulations of CS creation in the corona for
different field approximations (Forbes and Priest,
1984; Rickard and Priest, 1994; Podgorny and
Podgorny, 1998; Archontis et al., 2006). The CS
creation and energy storage in the CS magnetic field
before a flare has been demonstrated in 3D MHD numerical simulation (Bilenko et al., 2002). For these purposes the active region magnetic field is approximated by the field of magnetic dipoles placed under the photosphere. This approximation permits to show the energy accumulation of $10^{33}$ erg before the Bastille flare. But such an approximation does not include all peculiarities of the photospheric preflare magnetic field, and CS location cannot be obtained with high degree of precision. To improve precision a method of setting the observed photospheric magnetic field as a boundary condition is developed. Here we present the result of simulation of CS creation in the real active region that appears due to the real photospheric disturbances observed before a flare. In this simulation no assumptions about the flare mechanism are done.

2. Numerical simulation

The AR 0365 has been chosen for simulation since its magnetic field is not very complicated. The observed change of the photospheric magnetic field leads to evolution of the coronal magnetic configuration (Podgorny and Podgorny, 2006). The temporal system of resistive 3D MHD equations for compressible plasma is solved in the computational domain $(0 < x < 1, 0 < y < 0.5, 0 < z < 1)$ in dimensionless units. $L_0 = 1.2 \times 10^{10}$ cm is used as the length unit. $Y$ axis is directed from the Sun. $X$ is directed to the west, and $Z$ is directed to the south. The photospheric boundary ($y = 0$, $0 < x < 1$, $0 < z < 1$) of numerical domain contains the active region AR 0365. The observed line-of-sight magnetic field component distribution on the photosphere ($y = 0$, $0 < x < 1$, $0 < z < 1$) obtained by SOHO MDI is used for setting initial and boundary conditions.

The initial magnetic field in the computational domain is set three days before the flare on May 27, 2003, because observations (Ishkov, 2001) show that the photospheric magnetic field begins to change in 1–2 days before the flare. The potential field is taken for setting the initial condition, because three days before a flare there are no essential disturbances in the corona, and so the currents can be neglected. The potential field is calculated in the computational domain by solving numerically the Laplace equation using a finite-difference scheme on the same grid as for MHD equations. An inclined derivative is employed as a boundary condition on the photosphere boundary, since the line-of-sight field component is generally inclined at some angle to the photosphere. The field on the nonphotospheric boundary is small and does not influence the solution of the Laplace equation that is verified by solving with different types of conditions on the nonphotospheric boundary.

For setting boundary conditions, it is necessary to use magnetic vector evolution on the photosphere. However, SOHO MDI magnetic maps give data only for the magnetic component directed along the line-of-sight. Magnetic components parallel to the photosphere are taken from distribution of the potential magnetic field, that is calculated also by numerical solving of the Laplace equation. Such an approximation is possible, because CS is located high in the corona, so the CS magnetic field does not influence the photospheric magnetic field strongly.

In the chosen corona region with the height $\sim 0.1 R_\odot$, the plasma density and the temperature do not strongly change in space. So the initial plasma density and the temperature are set to be constant in space. Their values are corresponded to conditions in the low corona $\rho_0 = 10^8$ cm$^{-3}$ and $T_0 = 10^6$ K. The initial velocity is taken to be zero.

The process of CS creation takes place sufficiently high, $\sim 1/20 R_\odot$, and the plasma density change on the photospheric boundary at $\beta \ll 1$ hardly influence CS creation. The plasma density $\rho$ on the photosphere is set to be constant, equal to $\rho_0 = 10^8$ cm$^{-3}$. The normal to the photosphere derivative of the temperature is set to be zero ($\partial T/\partial n = 0$). The condition for the plasma velocity on the photosphere is $\partial V/\partial n = 0$. It is assumed that the currents on the nonphotospheric boundary may be neglected. Therefore, $B$ components parallel to the nonphotospheric boundary are set from rot $\mathbf{B} = 0$ condition. The normal $B$ component is set from div $\mathbf{B} = 0$ that is found automatically from solution of MHD equations, if a difference scheme conservative relative to magnetic flux is used. The free-exit conditions on the nonphotospheric boundary are approximated as $\partial \rho/\partial n = 0$, $\partial T/\partial n = 0$, $\partial V/\partial n = 0$.

The system of 3D MHD equations is solved numerically by an absolutely implicit scheme (Podgorny and Podgorny, 2004). The scheme is conservative relative to the magnetic flux. It means that instead of a magnetic field vector, the averaged magnetic fluxes per unit of square through boundaries of grid cells are used. The total flux through each cell boundary remains the same at passing to
the next time step. It means, that the finite-difference analog of $\text{div } \mathbf{B}$ is equal to zero, if $\frac{1}{2} \text{div } \mathbf{B} / C_{138} = 0$ for the initial field. This scheme has been realized in the PERESVET code. The calculations are carried out with a grid $101 \times 51 \times 101$.

The finite-difference analog of $\text{div } \mathbf{B}$ for the initial potential field calculated by solving numerically of the Laplace equation is equal to zero with precision of $0.5 \times 10^{-3}$ in dimensionless units. This precision of $\frac{1}{2} \text{div } \mathbf{B} / C_{138} = 0$ is preserved during entire time of calculations. The equality of $\frac{1}{2} \text{div } \mathbf{B} / C_{138} = 0$ is controlled at each time step.

The 3D numerical MHD simulation (Podgorny and Podgorny, 1992, 2001) has shown that CS appears in SL vicinity due to magnetic disturbances focusing. The current density in CS increases with time. The current density maximum is situated on SL. The current is directed along this line. SL has been found as a line passing through the position of the current density maximum. The coronal magnetic field configuration above AR 0365 contains several SL. However, the calculations show that CS appearing in the vicinity of SL that intersects the plane $z = 0.6$ on the interval $0.2 < x < 0.5$ is the most powerful. Here, we restrict ourselves only to analyze this SL and compare calculation results with the biggest radio-emission flare burst observed on the SSRT radio telescope.

The analysis of magnetic field behavior in planes perpendicular to the photosphere shows that the best conformity of a magnetic configuration to the CS magnetic field is revealed in the plane $z = 0.6$. The magnetic field configuration before the flare is shown in Figs. 2a and b. Here, the magnetic lines located behind the $z = 0.6$ plane are indicated by dashed lines. The zero X-point in the plane perpendicular to SL must coincide with the point of SL intersection of this plane. However, the zero X-point in the $z = \text{const}$ plane does not coincide with the point of SL intersection of this plane (Fig. 2(b)), because SL is not normal to this plane. It means that the current density maximum in the $z = \text{const}$ plane does not coincide exactly with the magnetic X-point. Such an exact coincidence takes place in $X_1 Y_1$ plane (Fig. 2(c)). Here $Z_1$ axis is tangential to SL in the point of the plane intersection; $X_1$ and $Y_1$ axes are perpendicular to this line. Coincidence of the current maximum and the magnetic X-point in this plane proves correctness of calculations. It is reasonable to conclude that the maximum of plasma heating must occur in this point during a flare, because the current density maximum is situated in this place.

The computational domain moves with an active region on the solar disk due to Sun rotation. The calculations show that only a negligible shift of the current density maximum inside the computational domain occurs in the time interval starting 12 h before the flare. This fact permits to obtain the maximum current density coordinates at any time within this interval in spite of the different time scales in calculations and in the reality.

3. Flare radio emission

The May 27, 2003 flare at 02:53:28.54 has produced the strong increase of the brightness temperature observed by the SSRT radio telescope.
at the 5.2 cm wave. This wave belongs to the high frequency continuum appearing simultaneously with the flare X-ray emission (Benz et al., 2005). The observed maximum of the brightness temperature was $1.24 \times 10^7$ K. Distribution of the radio emission intensity of the flare on May 27, 2003 at 02:53:28.54 in the AR 0365 is presented in Fig. 3(b) in the figure plane (perpendicular to the line-of-sight). The magnetogram of the magnetic field component along the line-of-sight is also shown. The SOHO MDI magnetogram (http://soi.stanford.edu/magnetic/index5.html) is used. Heliocentric coordinates of the brightness temperature maximum are S6.58 W5.97. This maximum is indicated by the cross in Fig. 3(b).

Coordinates of singular point in the computational domain are $(x = 0.25, y = 0.25, z = 0.6)$. Its heliocentric coordinates on May 27, 2003 at 02:53:28.54 are S7.541 W4.692. $B_{\text{normal}} = \text{const}$ lines calculated in potential approximation on the photosphere are shown in Fig. 3(a). Lines of equal intensity of the radio emission and the flare magnetogram are shown in Fig. 3(b) for comparison. The position of the flare is marked by a cross in both figures. The cross in Fig. 3(a) is a projection of the point $(x = 0.25, y = 0.25, z = 0.6)$ on the photosphere along the normal, and the cross in Fig. 3(b) is the position of the radio emission maximum. Positions of the both maxima coincide with accuracy about 1°. This coincidence is in agreement with the electrodynamical solar flare model. The inexactitude does not surpass the accuracy of setting boundary conditions from the photospheric magnetic field, the accuracy of calculation, and accuracy of obtaining coordinates on the solar disk.

4. Conclusion

The comparison of the results of numerical MHD simulations and radio emission observations demonstrates a convincing evidence of correctness of the electrodynamical solar flare model based on energy accumulation in the magnetic field of CS appeared above an active region. These results demonstrate that MHD simulations permit tracing the flare position from analyzing preflare photospheric magnetic maps.

Acknowledgements

Authors acknowledge fruitful cooperation with A.T. Altyntsev, V.V. Grechnev, and A.I. Hlystova. The work was supported by Russian projects of RFBR Nos. 06-02-16006, 05-07-90147, 04-02-39003.

References