MHD WAVES AND SHOCKS GENERATED DURING MAGNETIC FIELD RECONNECTION

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Abstract. We use a 2D MHD model of magnetic field reconnection to investigate if and how bursts of reconnection activity, changes of the magnetic field and shock wave generation are related. We found that major bursts of power dissipated into Joule heat occur during topological transitions of the magnetic field structure. These bursts are followed by shocks and waves. Along the plasma outflow jet not only MHD waves, but also ion-sound shocks are formed. After the phase of more or less quiet reconnection (Petschek-type) the tearing mode produces plasmoids. The interactions of these plasmoids are associated with further bursts of the reconnection activity and a complex structure of shock waves. Finally, all these processes are discussed as possible sources of various radio bursts.

Key words: solar flares - magnetic reconnection - MHD waves

1. Introduction

It is commonly accepted that the energy release in solar flares and related phenomena (e.g., acceleration of particles and emissions in a broad range of energies) is due to the conversion of energy stored in the magnetic field by the process of reconnection of magnetic field lines (Priest and Forbes, 2000). The soft and X-ray observations made by the YOHKOH and RHESSI satellites provide us with evidence of magnetic field reconnection (Tsuneta et al., 1992; Masuda et al., 1994; Shibata, 1999; Yokoyama et al., 2001; Krucker et al., 2003; Lin et al., 2003; Chen et al., 2004). Ugai (1986) showed that the fast reconnection of the Petschek type (Petschek, 1964) can be triggered by a localized anomalous resistivity. On the other hand, Odstrčil and Karlický
(1997) modelled the triggering of the magnetic reconnection by shock waves from distant flares. Tanuma et al. (2001) used this concept of triggering by shock waves and found that the Petschek reconnection occurs immediately after the secondary tearing instability (Furth et al., 1963).

Kliem et al. (2000) have shown that for a sufficiently long current sheet the reconnection process has a bursting character given by the tearing instability. As shown by Shibata and Tanuma (2001) this process leads to a multi-scale cascade in which the current sheet is fragmented to smaller and smaller plasmoids which subsequently interact and coalesce to larger ones. Recently, Tanuma and Shibata (2005) have proposed internal shocks (tearing mode) in the magnetic reconnection jets as possible causes of the acceleration of particles in solar flares.

In addition to studies devoted to the reconnection process itself, there are attempts to identify the radio emissions corresponding to the reconnection process (Kliem et al., 2000; Aurass et al., 2002; Karlický, 2004; Karlický and Bártta, 2004; Bártta and Karlický, 2005a; Khan and Aurass, 2006).

In the present paper, we first describe global properties of bursting reconnection, i.e., peaks of reconnection activity associated with the topological changes of the magnetic field that are followed by shocks and waves. Then these waves are analysed in detail. Finally, we search for radio signatures which could be connected with the reconnection processes presented in this study.

2. Model

We describe the evolution of the magnetized plasma by the compressible resistive one-fluid MHD equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0
\]

\[
\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = -\nabla p + j \times B
\]  \hspace{1cm} (1)

\[
\frac{\partial B}{\partial t} = \nabla \times (u \times B) - \nabla \times (\eta j)
\]

\[
\frac{\partial U}{\partial t} + \nabla \cdot S = 0,
\]
where the energy flux $S$ and auxiliary variables (plasma pressure $p$ and current density $j$) are defined by the formulae (see, e.g., Kliem et al., 2000):

$$ \nabla \times B = \mu_0 j $$

$$ U = \frac{p}{\gamma - 1} + \frac{1}{2} \rho u^2 + \frac{B^2}{2\mu_0} \quad (2) $$

$$ S = \left( U + p + \frac{B^2}{2\mu_0} \right) u - \frac{(u \cdot B)}{\mu_0} B + \frac{\eta}{\mu_0} j \times B $$

Although the MHD model is not capable to describe the non-ideal effects (resistivity) consistently they are included phenomenologically: we change the resistivity $\eta$ dynamically to an anomalous value whenever the drift velocity $v_D$ exceeds a given threshold $v_{cr}$ (Kliem et al., 2000):

$$ \eta(r, t) = \begin{cases} 0 & : |v_D| \leq v_{cr} \\ \frac{C(|v_D(r, t)| - v_{cr})}{v_0} & : |v_D| > v_{cr} \end{cases} \quad (3) $$

Here we assume, that the onset of anomalous resistivity is caused by the instability of the electron stream forming the electric current at high electron-ion drift velocity. Of course, in such a large-scale simulation one can not resolve the typical width of the dissipative current sheet ($\approx 10 m$, Litvinenko, 1996), but we still believe that the regions where the enhanced resistivity takes place in our model can be interpreted as dissipative regions in the sense of the concept of fractal reconnection proposed by Shibata and Tanuma (2001).

At the very beginning the system consists of the symmetric vertical Harris-type current sheet in the middle of the 2D rectangular computation domain. At $t = 0$, a limited area surrounding the origin is perturbed by anomalous resistivity for a short time. Then the evolution is numerically simulated using the 2D Lax-Wendroff scheme with free boundary conditions on the upper part and (due to the sheet symmetry) on both left and right sides. Symmetric ($Q(y) = Q(-y)$) and anti-symmetric ($Q(y) = -Q(-y)$) relations are respectively used for quantities ($Q$) $\rho, u_x, B_y, U$ and $u_y, B_x$ at the bottom part of the boundary. This choice ensures a vertical magnetic field at the bottom boundary, and it is equivalent to a fixed boundary simulating the presence of the dense solar photosphere.

For convenience, throughout the simulation we use dimensionless variables, namely, the spatial coordinates $x$ and $y$ are expressed in units of the
Figure 1: Five subsequent snapshots of the current sheet dynamics between $t = 1475\tau_A$ and $t = 1536\tau_A$. The upper panels show the evolution of the magnetic field (black contours) and the current density (grey-scale). The lower panels depict the temporal variations of the dissipated power integrated over the reconnection volume. The double peak of the dissipated power is related to the two magnetic islands (plasmoids) emerging and subsequently coalescing near the point $[0L_A, 80L_A]$ (upper panels). The lower-right panel is the detailed view onto the area marked by the dashed box. The vertical dashed lines point to the time instants corresponding to upper panels.

current sheet width $L_A$ and time in Alfvén transit time $\tau_A = L_A/V_{A,0}$. $V_{A,0} = B_0/\sqrt{\mu_0\rho_0}$ is the asymptotic value ($x \to \infty$) of the Alfvén speed at the initial state ($t = 0$). See papers by Karlíčký (1988) and Kliem et al. (2000) for details.

3. Results

The system (1) was solved inside a $(-18, 18) \times (0, 90)$ box (length units are in the half-width of the current sheet $L_A$), i.e., on 801x2001 grids, in the time interval 0–1600 $\tau_A$. The asymptotic value ($x \to \infty$) of the plasma beta at the initial state ($t = 0$) is $\beta = 0.15$. 


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The global evolution of the perturbed current sheet is as follows (see the time profile of the dissipation power in lower-left panel of Figure 1): Due to an initial (0–10 $\tau_A$) increase of the anomalous resistivity around the origin [0.0 $L_A$, 0.0 $L_A$] the reconnection starts. It results in plasma inflows from both sides of the current sheet, which leads to a compression of the current sheet. As a consequence, a dissipative region (an X-point) moves rapidly from the origin to its new (‘self-consistent’, see discussion in Karlický and Bártá, 2006) location in [0$L_A$, 10$L_A$] at $t \approx 250\tau_A$. Below this X-point a loop-like (arcade-like when taking into account the invariant dimension) structure is formed. Then, after some short transient state a long period of quasi-stationary regime of the reconnection follows during 300–1000 $\tau_A$ (see the dissipation power profile in Figure 1). During this period the formed arcade of loops slowly grows (the X-point moves up-wards) as a consequence of newly reconnected magnetic flux and due to the fact, that magnetic loops are “rooted” in the bottom boundary ($u_x(x,0) = 0$) as consequence of the chosen bottom-part boundary condition. This behaviour is consistent with general flare models as well as with observations. The final phase ($t \geq 1000\tau_A$) of the computation is highly intermittent with several interactions of newly emerged plasmoids.

In order to have a simple quantitative measure of reconnection energetics we use the power dissipated into the Joule heat:

$$D = \int_{\text{Box}} \eta(x,y)j^2(x,y)dx dy,$$

as a proxy for the reconnection activity. The bursty and highly intermittent nature of the reconnection process is clearly visible in Figure 1 (lower-left panel) . We found, that the peaks of dissipated power are closely related to topological transitions of reconnecting magnetic fields. It is clearly pronounced at $t = 250\tau_A$ when a new X-point is formed at $y \approx 10L_A$ leading to a burst of reconnection activity. As the reconnection proceeds through a more or less quiet phase of the Petschek-type process for $t \in (250\tau_A, 950\tau_A)$, the compressed current sheet eventually becomes long enough for the tearing mode instability to set in and several plasmoids are formed. These plasmoids interact and these interactions (new formations and coalescences) are accompanied by further enhancements of the dissipative power (see the many bursts in the lower-left panel at the advanced phase of simulations, $t \geq 950\tau_A$). Figure 1 displays a series of five subsequent snapshots between
Figure 2: Snapshot of reconnection at $t = 230\tau_A$. Left: magnetic field (lines) and current density (grey-scale); right: density (grey-scale) and velocity (arrows) structures. The panels show a continuation of the jet-like plasma outflow with the sound shock at $y \in (60L_A, 65L_A)$.

Figure 3: As in the previous figure, but at $t = 285\tau_A$. The panels show the MHD shock (approximately circular arc) centred around the point $[0.0L_A, 10.0L_A]$ with radius $\approx 35L_A$. 
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t = 1475τA and t = 1536τA, and demonstrates how the complicated temporal behaviour of the dissipated power is related to the formation and subsequent merging of two new magnetic islands.

Bursts of reconnection activity measured by the dissipated power as well as other significant features of reconnection (e.g., mass flows) influence strongly the environment in the vicinity of the reconnection process and shocks and waves of various types can be generated. This is demonstrated in Figures 2 and 3. The left panels of these figures show the magnetic field lines (black contours) and the corresponding electric current densities (grey-scale; darker and lighter areas represent positive and negative values, respectively, neutral grey corresponds to zero current density). The right panels show the plasma density (grey colours, white refers to enhanced densities and vice versa) and plasma velocity (black arrows).

4. Detailed analysis of reconnection-generated waves and shocks

In this section we demonstrate the propagation and basic properties of the waves that are generated during our reconnection experiment (Figures 2 and 3). In order to gain an insight into the nature of the waves we have analysed the profiles of several quantities along appropriately chosen 1-D paths in the direction of the wave propagation for two subsequent time instants. The results are presented in Figures 4 and 5.

4.1. The sound shock

Figure 4 shows variations of plasma density (solid black), temperature (solid grey) and square of magnetic field strength (dashed black) in the shock propagating along the y-axis direction around t = 230τA (cf., Figure 2); the value axis for these quantities is displayed at the left. Further, the projection of plasma velocity to the wave propagation direction is presented (dashed grey) in order to evaluate the wave phase speed in the plasma reference frame; its scale is shown at the right ordinate. As can be seen, all quantities show wave-related variations. The path (a line) along which the quantities were analysed is given by the relation x = 4.0, the beginning and end of the path correspond to the points [4.0L_A, 50.0L_A] and [4.0L_A, 80.0L_A]. The profiles of studied quantities have the typical shape of a shock wave.
Figure 4: Plasma density (solid black), temperature (divided by the plasma beta for convenient scaling; solid grey) and square of magnetic field strength (dashed black) in the direction of wave propagation, scales in used dimension-less units are according to the left ordinate; and the profile of plasma velocity in projection to the direction of wave propagation (dashed grey), scaling according to the right ordinate. Two subsequent profiles in direction of the wave motion taken at $t = 227\tau_A$ and $t = 233\tau_A$.

Figure 5: Two subsequent profiles in direction of the wave motion taken at $t = 282\tau_A$ and $t = 288\tau_A$. Meaning of the curves is as in the previous figure.

The density, projected velocity and temperature are affected by the wave motion, while the magnetic field remains almost constant over the wavefront. The phase velocity at the (unperturbed) plasma reference frame is $v_{ph} = 0.735V_{A,0}$ which corresponds to $v_{ph} = 2.45C_s$, where $C_s$ is the local sound speed. The density and plasma velocity jumps are $\Delta n = 0.23$ and $\Delta v = -0.084$ respectively, both in our dimensionless units. As can be seen on the upper panel of Figure 2 the wave propagates almost parallel along the magnetic field lines. To sum up, all results of this analysis show, that the wave is an ion-sound shock with the (sound) Mach number $M_s = 2.45$. 

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4.2. The MHD Shock

Figure 5 shows variations of density, temperature, magnetic field strength and projected velocity in the fast disturbance propagating outwards almost radially from the point \([0.0L_A, 10.0L_A]\) around \(t = 285\tau_A\) (cf., Figure 3). The direction selected to get the parameter profiles shown in Figure 5 is a line defined by relation \(y = 4x + 10\), thus going through the point \([0.0L_A, 10.0L_A]\), where the wave presumably originates due to the localised Joule heat deposit at the newly created X-point (see the dissipated power time-profile in the bottom panel of Figure 1). The beginning and the end of the path correspond to the points \([0L_A, 10L_A]\) and \([18L_A, 82L_A]\). All quantities show wave-related variations. The phase velocity is \(v_{ph} = 2.42V_{A,0}\), the local Alfvén speed \(V_A = 0.946V_{A,0}\), which together with the steep profile indicate that the perturbation under study is a MHD shock with the Alfvén Mach number \(M_A = 2.56\).

In Figure 6 we present in more detail the kinematics of the MHD shock and the associated perturbation in the current sheet. The MHD wave propagating outside the current sheet is a quasi-longitudinal fast-mode shock. In the downstream shock region the plasma flow is directed away from the current sheet \((u_x > 0)\), and is characterized by the enhanced magnetic field, temperature, and density (Figure 5). We have measured the position, \(y(t)\), of peak values of these parameters along the line \(x = 10\). In Figure 6a we show the \(y(t)\) measurements of the peak values of the density \(\rho\) and flow speed \(u_x\), as well as the \(y(t)\) positions of the beginning and the end of the \(u_x\) perturbation. The difference between the beginning and the end of the perturbation, defining the width of the perturbation increases in time, similarly as in the case of the freely propagating simple wave (Landau and Lifshitz, 1987). However, the amplitude of the simple wave should decrease with the distance, whereas in our case the amplitude of the wave increases (see the grey line in Figure 6c), implying a continuous supply of energy.

Although the associated perturbation in the current sheet shows a quite similar kinematics (Figure 6b), it has completely different physical characteristics than the wave outside the current sheet. The disturbance within the current sheet is characterized by increased temperature and decreased density at the location where the outflow magnetic field shows the largest gradient (stronger field downstream). This implies that the current sheet perturbation cannot be considered as a compression wave.
Figure 6: a) Kinematics of MHD shock. b) Kinematics of the associated current sheet perturbation. c) Velocity of the reconnection inflow, and the amplitude of the $u_x$ flow velocity in the shock downstream region. Meaning of the curves is given in the legend.

The two disturbances, the one inside and and the one outside the current sheet, obviously are tightly related. They are launched at about the same time, both show an initial acceleration, they propagate at the same velocity, and show a weak deceleration as they approach the upper edge of the numerical box. The initiation of the disturbance is closely related to the impulsive peak of dissipated energy at $t \approx 250$. To inspect in more details the launch of the disturbance, we checked the change of the reconnection rate in time. In Figure 6c we show (the black line) the change of the velocity by which the plasma flows into the diffusion region. Comparing Figure 6b with Figure 6c, one finds that the perturbation is launched during the period characterized by the increasing inflow speed, and is accelerated during the inflow peak. The increase of the inflow speed causes widening of the angle between the slow mode shocks that bound the reconnection outflow.
(Vršnak and Skender, 2005), as can be seen in Figure 3. That results in an increase of the magnetic field strength in the reconnection outflow, implying that a gradient of the magnetic field is created, driving the wave-like perturbation to propagate along the current sheet. The heating caused by the associated current leads to increased pressure and plasma expansion in the $x$-direction, i.e., perpendicular to the current sheet. As a result the hot density depletion travels along the current sheet, accompanying the propagating magnetic field gradient. On the other hand, this moving “bulb" drives the compressional quasi-longitudinal fast-mode MHD wave in the external region. Such a pattern is consistent with the pattern found by Volonskaya et al. (2003) in their analytical study of the time varying reconnection (see Figure 7 therein).

5. Associated radio emissions

We have found that bursts of energy release in flare reconnection produce shock waves. Most of them are MHD shocks, but also the sound shock waves are present.

There are several dissipative regions at later phases of our reconnection experiment as a consequence of secondary tearing and interactions of plasmoids. Each of these dissipative regions can produce shocks and waves as well. The waves propagating from these locations can positively interfere and contribute to the flare shock that is formed at some distance from the reconnection site. The amplitude of this shock possibly further increases as the shock propagates to the outer corona where the density and magnetic field decrease. Such a strong shock can become a source of radio emission detected as a type II burst. In this case the shock that causes a type II radio emission is initiated by the flare and is independent of the CME front and travels through the already-existing CME structure faster than that of the CME leading front (see observations of, e.g., Wagner and MacQueen, 1983; or Vršnak et al., 2006).

Although the particle velocity distribution is not computed here within the MHD model, it is commonly accepted that particles are effectively accelerated in the electric fields at the reconnection sites (e.g., Aschwanden, 2002), or in the MHD turbulence and shocks in reconnection jets (e.g., Miller, 1997; Tanuma and Shibata, 2005). Thus, if we consider beams of accelerated electrons which are trapped in plasmoids, then the so called
drifting pulsation structures can be explained (Kliem et al., 2000; Karlický, 2004). Furthermore, turbulent conditions in the reconnection jet are suitable for the generation of the narrowband dm-spikes and lace bursts as shown by Bártá and Karlický (2001 and 2005a).

Now, let us consider the case of the sound shock wave presented in Figures 2 and 4. Here the question arises if this type of shock wave can also be registered at radio waves. This sound shock wave has a very regular density structure. Bártá and Karlický (2005b) studied the radio wave propagation through such regular structures using the wave optics approach and found that the regular structures can cause 'diffraction' patterns on observed radio spectra. The corresponding radio emission was identified with the zebra burst.

6. Conclusions

Reconnection of magnetic fields is commonly supposed to be the main mechanism of energy release in solar flares. Keeping this in mind we have studied numerically the 2D MHD model of magnetic reconnection and found that:

1. Sudden bursts of power dissipated into Joule heat occurs during each change of magnetic field topology. In particular, formation and subsequent interaction (coalescence) of plasmoids created during the late phase of this numerical experiment when turbulent reconnection (see Shibata & Tanuma, 2001) takes place lead to a bursty and intermittent character of temporal evolution of dissipated power.

2. Each of these bursts of dissipation comes only from a limited extent of the reconnection volume and thus the dissipated energy becomes a source of shocks and waves of various modes via the following mechanism: the pressure pulse together with associated changes of the reconnection rate create wave-like low-density/high-temperature perturbations propagating along the current sheet. These “bulbs” released impulsively from the dissipation areas then drive the shocks propagating through the external region.

Our study is in agreement with the recent work by Tanuma and Shibata (2005), who found internal shocks (tearing mode) in the reconnection outflow jets. The present paper generalizes their view, as other wave modes
(fast-mode MHD and ion-sound shocks) were found and also the mechanism of their generation has been clearly identified. Another new aspect of our study is that waves generated during the bursting reconnection are not limited to the reconnection outflows but can propagate outside the reconnection zone. If we recall the possible application of the model to theory of solar flares the last statement means, that the mechanism of wave generation presented in this paper can account for a flare related shock which is independent from the one created by the associated CME front. Such shocks, propagating behind the leading edge of CMEs, were really observed (e.g., Wagner and MacQueen, 1983; Vršnak et al., 2006).

Finally, we studied possible observational effects that could be found in solar radio spectra if the model is applicable for solar flares. As was already mentioned, the model can explain an observed type II emission related to the flare shock independent from the CME front. Further, we were able to trace the development of the Fourier power spectra of the density variations within this study. It was shown, that it gradually gains a power-law distribution with spectral index $s \approx -2$. As it has been investigated in our earlier studies (e.g., Bártta and Karlický, 2005a) such a turbulent spectrum may be reflected in observed radio spectra as lace bursts or decimetric spikes. Also, the regular density distribution in the ion-sound shock front found in our numerical experiment may cause a "diffraction" of radio waves similarly as in crystallography (see Bártta and Karlický, 2005b). This recently studied effect may lead to strong frequency modulation of the received radio signal which resembles a zebra pattern in observed radio spectra. The relations between the model and its possible observational consequences may be used as tests of general applicability of the concept of magnetic reconnection to the theory of solar flares, and moreover, can provide us with useful tools for remote solar plasma diagnostics in the radio wavelength range.

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