THEORETICAL AND OBSERVATIONAL FEATURES OF MAGNETIC RECONNECTION

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Abstract. We present general solutions of the time–dependent Petschek–type model of magnetic reconnection for a compressible plasma. The disruption of a tangential discontinuity because of a localized decrease of the resistivity leads to the generation of several MHD wave modes. By solving the Riemann problem, the behavior of these modes can be visualized. Additionally, disturbances of the ambient plasma environment by the propagating shock structures can be modeled. As an observational feature, the determination of the reconnection rate in a two–ribbon flare is presented.

Key words: Magnetic reconnection – Magnetohydrodynamics – Sun

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1. Introduction

Magnetic reconnection is a powerful theory to explain the conversion of magnetic energy into kinetic and thermal energy. This process is thought to occur in various plasma environments like planetary magnetospheres, in stellar atmospheres and in fusion devices. The first model for “fast” reconnection was proposed by Petschek (1964), where he described the behavior of magnetic flux tubes, which have been reconnected across a current sheet. The reconnection of magnetic field lines is caused by some finite conductivity in a localized region, generating a dissipative electric field tangential to the current sheet. According to the general Riemann problem, the tangential electric field leads to the decay of the tangential discontinuity into a set of MHD waves propagating along the current layer forming a thin boundary layer. In order to satisfy all conservation laws across the boundary layer, two shock waves and three discontinuities are needed.

In the present paper, the structure of the boundary layer is shown for a given reconnection electric field. Additionally, the perturbations in the magnetic field and the plasma flow in the inflow region are calculated. For this purpose, the analytical model of time–dependent Petschek–type magnetic reconnection developed by Heyn and Semenov (1996) is used. It allows the presentation of the plasma disturbances as convolution integrals of the reconnection electric field and an integration kernel in time.

As an example, the reconnection rates occurring in a two–ribbon flare are estimated. At the Sun, magnetic reconnection is the only viable mechanism that can account for many well-known flare characteristics, such as the flare loop expansion, the observed, apparent Hα and EUV flare ribbon separation, the cusp-shaped structures observed in soft X-rays, and the amount of energy released. Since until now only a single direct observation of a plasma inflow into the reconnection region has been made (Yokoyama et al., 2001), an indirect method is needed to determine the reconnection rate in solar flares from observations. Forbes and Priest (1984) and Forbes and Lin (2000) pointed out that the local reconnection rate is directly given by the electric field \( E \) at the reconnection site. Furthermore, they derived a simple
relation between the local reconnection rate and the apparent motion of the chromospheric Hα flare ribbons, that holds in a two-dimensional configuration with translational symmetry along the third dimension. According to this relation it is possible to determine the reconnection rate in solar flares as the product of two observables, namely, the flare ribbon separation speed \( v \), and the magnetic field strength component \( B \) perpendicular to the solar surface at the current ribbon location (\( E = v \times B \)). In order to verify this hypothesis, a large two-ribbon flare (GOES-class M3.9), which occurred on November 18, 2003 in NOAA Active Region 501 (S02°, E37°), is analyzed.

2. **Perturbations and shock structure caused by reconnection**

The original model of Petschek (1964) is steady-state and completely symmetric with respect of the current sheath, with the only exception of the magnetic field orientation. In a series of papers, the original Petschek model has been generalized for time-varying phenomena, skewed magnetic fields, and a reconnection line of finite length (Semenov et al., 1992). Subsequently, this theory was generalized for the inclusion of finite tangential plasma velocities and arbitrary densities (Semenov et al., 1995), and, in addition, was applied to conditions at the terrestrial magnetopause (Biernat et al, 1998).

In the following, according to the geometry at the Sun, antiparallel magnetic fields are studied, which are conveniently assumed (as in Petschek’s approach) to be separated by an infinitely thin current sheet. The background magnetic fields and the total pressure are assumed to be constant, while the velocity is zero in lowest order in the inflow region. The problem can be separated in two different steps. Firstly, we can evaluate the tangential components of the magnetic field and the plasma flow from the non-linear system of MHD equations for the zero order by assuming that these quantities are constant. If they are constant, they can be found from the Rankine–Hugoniot relations directly. In a second step, we can determine the normal components from the linearized system of MHD equations in the first order approximation. This is the direct solution of the Petschek–type model of reconnection (e.g., Biernat et al., 1987). To calculate time series of
the magnetic field and plasma flow components, which correspond to satellite measurements, we use the Cagniard–deHoop method (Heyn and Semenov, 1996). The solution of the direct problem is obtained in terms of a displacement vector, from which the magnetic field and plasma flow parameters in Fourier-Laplace space can be derived. The Cagniard–deHoop method allows one to perform the inverse Laplace transform analytically, which gives the normal component of the magnetic field perturbations in real space as the convolution integral,

\[ B_z^{(1)}(x, z, t) = \int_0^t G(x, z, t) E(t - \tau) d\tau, \]

where \( G(x, z, t) \) is the integration kernel, which depends on the magnetic field configuration and the location of the reconnection site, and \( E(t) \) is the reconnection electric field. For the plasma flow and the tangential component of the magnetic field, similar expressions can be found.

As already discussed, a tangential discontinuity disturbed by reconnection decays into a set of Alfvén waves (A), slow shock waves (S) and a contact discontinuity (C) in the center. In Fig. 1, the structure of the boundary layer is shown for \( B_u = 1 \) and \( B_l = -0.5 \), while the plasma beta is \( \beta_u = 0.1 \) and \( \beta_l = 3.4 \), respectively. Indices “u” and “l” denote the upper and lower half space. Also the disturbances in the \( B_z \)-component according to Eq. 1 are shown.

3. Reconnection rate in a two-ribbon flare

Reconnection rates that have been determined by using the simple Forbes-Priest relation (\( \mathbf{E} = \mathbf{v} \times \mathbf{B} \); Forbes and Priest, 1984) can be compared with the observed hard X-ray (HXR) flux, that acts as an indicator for the number of accelerated particles, and therefore is considered to be proportional to the energy release rate in a solar flare (e.g., Hudson, 1991). If the Forbes-Priest relation for approximating the local reconnection rate on the basis of two observable measures holds, then the temporal evolution of the derived reconnection rate should be correlated with the temporal evolution of the HXR flux, i.e., peaks in the derived reconnection rate should occur at the same
Figure 1: Distribution of the perturbation of the $z$–component of the magnetic field (left panel) and the shock structure for the parameters mentioned in the text.

Figure 2: Size and location of the flaring region at the time of the flare maximum (North up). The two bright, elongated structures are the separating Hα flare ribbons.
time as peaks in the HXR flux. In the following a short example of the analysis is given. The flare ribbon motion was tracked perpendicular to a locally defined magnetic inversion line, along a path that crossed a particular HXR burst site imaged by the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). To derive the temporal evolution of the local reconnection rate, the ribbon velocity was determined as the time derivative of the ribbon front distance from the inversion line. The distance profile was extracted from image time series in two different wavelengths, namely, \( H\alpha \) images, provided by the Kanzelhöhe Solar Observatory, and images in the 160 nm passband from TRACE, the Transition Region and Coronal Explorer. Furthermore, photospheric full-disk, line-of-sight magnetograms, provided by the Michelson Doppler Imager (MDI) on board the Solar and Heliospheric Observatory (SOHO) were used to achieve the magnetic field strength at the current ribbon front location.

Fig. 2 shows the size and the location of the flaring region at the time of the flare maximum. The two bright, elongated structures are the separating \( \text{H\alpha} \) flare ribbons. The northern ribbon was tracked
along the path shown in Fig. 3. The white contours represent the magnetic inversion line that lies in between the ribbons, whereas the black contours show the locations of the third HXR burst, designated as peak C, that occurred in the course of the flare. The results of the ribbon tracking procedure are shown in Fig. 4. The dark-gray vertical bars represent the duration of HXR burst C being crossed by path CN. The light-gray bars mark the duration of the other three HXR bursts A, B, and D. Panels (a) – (d) are not plotted after 08:22 UT in Hα, since afterwards the ribbon started to cool down. The black diamonds stand for the extracted ribbon front distance values (d), the photospheric magnetic field strength values at the current ribbon front location (B_p), and the product of the flare ribbon footpoint velocity v_f and B_p (E_0 = v_f B_p). The black solid lines represent the high-order polynom fit of the distance profile (d_fit), the time derivative of this profile (v_f), the polynom fit B_p,fit of the magnetic field strength B_p, and the derived local reconnection rate \( \tilde{E}_0 = v_f B_{p,fit} \). A comparison of panels (d) and (e) shows that the derived reconnection rate peak values coincide with peaks A and C in the RHESSI 20 – 60 keV HXR time profile (note that burst locations A and B were also partially crossed by tracking path CN). By tracking the flare ribbon front along paths that crossed the locations of HXR bursts A, B, and D, the other peaks in the HXR time profile also showed up in the derived local reconnection rate. This indicates, that the Forbes-Priest relation in fact appears to be an appropriate means to derive the local reconnection rate from the observable ribbon velocity and the photospheric magnetic field strength at the current ribbon front location.

4. Summary and Conclusions

We present an analytical model to describe the magnetic field and plasma behavior in the presence of magnetic reconnection. Additionally, an example for determining the reconnection rate for a two-ribbon flare is given, showing good agreement with the Forbes-Priest relation (Forbes and Priest, 1984).
Figure 4: Flare ribbon tracking results for path CN in Hα (left-hand side) and TRACE (right-hand side). a) Ribbon front expansion, b) ribbon velocity, c) magnetic field strength at ribbon front, d) derived reconnection rate, e) RHESSI 20 – 60 keV time profile.
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