THEORY OF ENERGY STORAGE AND RELEASE IN THE SOLAR CORONA

Thomas Neukirch

School of Mathematics and Statistics, University of St. Andrews, St. Andrews KY16 9SS, United Kingdom

ABSTRACT

The magnetic field is essential for energy storage and release in the solar corona. Slow (quasi-static) changes of the magnetic field at lower atmospheric levels (photosphere or sub-photosphere) build up energy which is stored in the coronal magnetic field. The coronal magnetic field evolves towards a point where it becomes unable to stay in (or close to) a state of (MHD) equilibrium, leading to sudden large-scale release of at least some fraction of the previously stored energy. The exact cause for the sudden onset of energy release is still a matter of debate and various possibilities have been suggested including a loss-of-equilibrium (”catastrophe”), ideal instability or magnetic break-out. All models invariably imply that at some point throughout the energy release phase thin current layers form in which magnetic reconnection takes place. Observations also indicate that topological and geometrical features of the magnetic field such as null points, separatrix surfaces and quasi-separatrix layers are associated with coronal energy release. One of the fundamental physical processes for coronal energy release is magnetic reconnection. Whereas magnetic reconnection is well understood on the larger (MHD) scale, there are still many open questions regarding the kinetic scale. Especially relevant for coronal energy release are the microscopic dissipation mechanisms responsible for reconnection and what role magnetic reconnection plays in the process of accelerating a large number of particles to high energies during flares, in particular because a substantial fraction of the energy is used to accelerate particles.

Key words: solar corona; magnetic fields; magnetic reconnection; flares.

1. INTRODUCTION

The magnetic field is the most important physical quantity for energy storage and release in the solar corona. On average the coronal magnetic pressure $B^2/2\mu_0$ is much larger than the plasma pressure p, implying a small plasma β, defined as the ratio of plasma to magnetic pressure. Therefore it is generally accepted that the energy

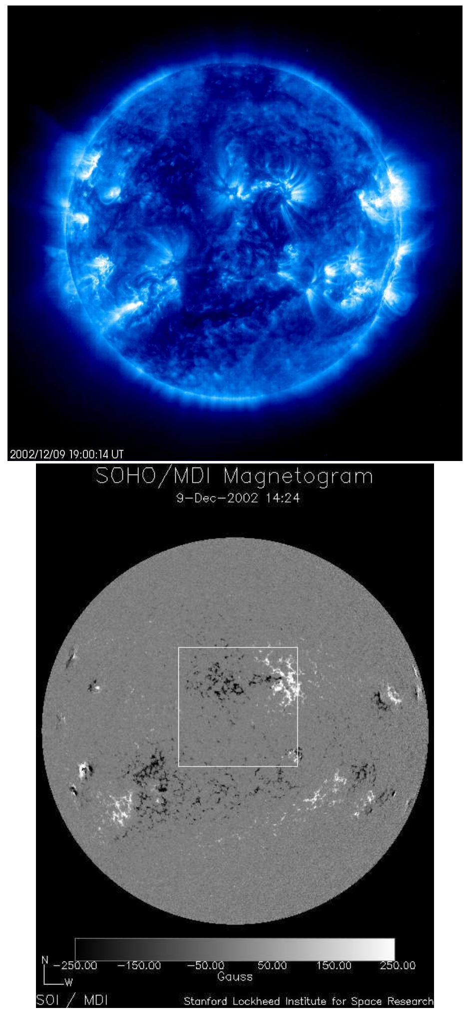

Figure 1. A comparison of a magnetogram (MDI) with coronal emission (EIT) showing a clear correlation between regions of strong magnetic field and enhanced emission. There is clear observational evidence that the magnetic field plays the most prominent role in energy storage and release in the solar corona.

Proceedings of the 11th European Solar Physics Meeting - The Dynamic Sun: Challenges for Theory and Observations, 11-16 September 2005 (ESA SP-596, December 2005)

released in the various activity processes occurring in the corona is stored in the magnetic field. Observationally, this is corroborated by the fact that regions of high activity and strong emission correlate extremely well with the regions of strong magnetic fields ("active regions"; see Fig. 1).

The build-up of energy in the coronal magnetic field usually occurs slowly, due to changes of the magnetic field at photospheric level. The time scale of the photospheric changes are of the order of hours or longer (at least on the larger length scales) whereas the response time of the coronal magnetic field is much shorter, namely of the order of the time needed by an Alfvén wave to cross the system under consideration (e.g. the length of a coronal loop). The exact time scale depends, of course, on the details of the system such as magnetic field strength and plasma density, but typically they are of the order of seconds. Therefore, the energy storage can usually be treated as quasi-static process.

Many models of large-scale coronal energy release have a slow quasi-static energy storage phase followed by a sudden onset of energy release caused by, for example, instabilities or loss-of-equilibrium. We will discuss some examples of such models in Sect. 2 . It has been suggested almost half a century ago that the topology of the magnetic field should play an important role in coronal energy storage and release (e.g. Sweet 1958). Modern observations indicate that indeed emission patterns observed during flares are associated with topological and/or geometrical properties of the magnetic field (e.g Demoulin et al. 1997; Metcalf et al. 2003). An overview of the part played by the topological or geometrical structure of the magnetic field in coronal energy storage and release will be given in Sect. 3. A fundamental process in all coronal energy release processes is played by magnetic reconnection. Whereas magnetic reconnection is quite well-understood on the macroscopic (MHD) level, the physical processes leading to the onset of reconnection and to the subsequent conversion of magnetic energy into bulk flow energy, thermal energy and non-thermal energy (e.g. high-energy particles) are still a matter of intense research. One of the most important questions for coronal physics is whether and how magnetic reconnection contributes to the acceleration of a large number of charged particles during solar flares, into which a substantial part of magnetic energy seems to be converted. The present state of the theory of particle acceleration in flares and some of the developments made in the kinetic theory of magnetic reconnection will be summarized in Sect. 4. The paper will conclude with a summary and discussion in Sect. 5.

2. MODELS OF LARGE-SCALE ENERGY RELEASE

On the largest scale coronal energy storage and release can be observe, for example, in the forms of coronal mass ejections (CMEs), prominence eruptions and flares.

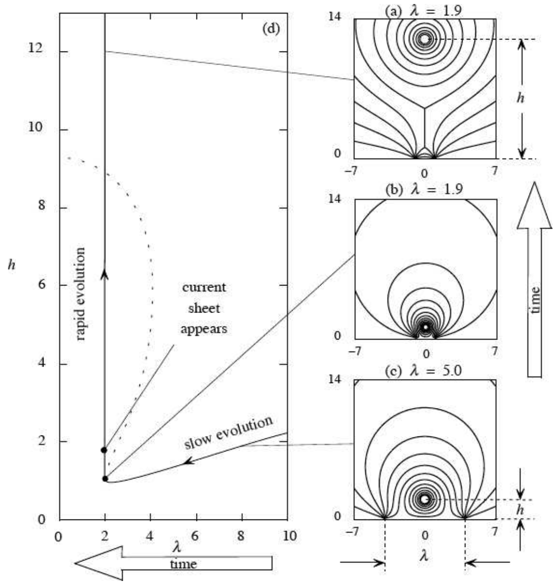

Figure 2. Catastrophe model of Forbes & Priest (1995). The three figures on the right show the magnetic field line configuration of the model for three different values of the control parameter λ. As indicated in the figure, λ is the distance between the two sources of the magnetic field. The figure on the left shows the dependence of the height of the flux rope of the model on the value of λ. For values of λ smaller than a critical value no nearby equilibrium exists and the system and the energy release process is initiated.

However, coronal activity is not limited to the largest scales and can be observed down to the smallest resolvable scales. In the majority of theoretical models the energy storage takes place on a slow (quasi-static) time scale. The fast energy release is then happening at some kind of onset point at which the system becomes destabilized in some way. Here we will only discuss three theoretical models. Recent detailed reviews of the theory of large-scale coronal energy release have been given, for example, by Forbes (2000), Priest & Forbes (2002) and Lin et al. (2003).

As a typical example of the "loss-of-equilibrium" class of models we refer to the two-dimensional model of Forbes & Priest (1995) (see Fig. 2). The model uses a potential field created by a positive and negative magnetic source on the photosphere, modified by a line current at a certain height h. In this particular model, the control parameter λ which represents the slow time dependence during the energy storage phase of the model, is directly related to the distance between the two photospheric sources. During the energy storage phase the distance between the flux sources is continually decreased. The height of the line current first decreases with decreasing λ, but starts to rise rapidly, just before a critical point (loss-of-equilibrium) is reached. For values of λ below the critical point, no equilibrium solutions exist *in the vicinity* of the previous solution. As can be seen in Fig. 2, the solution branch in the h vs. λ diagram bends backwards to larger values of λ before changing direction again for much larger heights. Since no equilibrium exists below the critical λ the system has to become dynamic, with the line current rising rapidly. Under ideal conditions a current sheet forms underneath the rising line current, in which under non-ideal conditions reconnection will set in eventually (see e.g. Forbes 1991). Amari et al. (2003) have tried to represent the philosophy of this 2D model in a 3D situation by first creating a current carrying flux rope by photospheric twist and subsequent reconnection (to obtain a change in topology resembling the 2D situation). They then drive the drive the regions of positive and negative magnetic flux towards the polarity inversion line, allowing for flux cancellation there, and find a behaviour which is qualitatively similar to that of the 2D model.

Ideal magnetohydrodynamic instabilities have for a long time been suggested as the cause for rapid coronal energy release, but mainly for compact loop flares (e.g. Hood & Priest 1979; Baty 1997; Baty et al. 1998; Gerrard et al. 2001). Over the past few years, however, it has been suggested (e.g Török et al. 2004; Kliem et al. 2004; Fan 2005) that the kink instability could be the cause of large scale eruptions as well. As an example we present a brief description of the model of Török et al. (2004) and Kliem et al. (2004) (see Fig. 3). The start configuration in this model is the class of non-linear force-free equilibria by Titov & Démoulin (1999). The equilibria contain a current-carrying curved flux tube, which is held in equilibrium by a surrounding potential field, but becomes kink-unstable for currents above a certain threshold. As the kink unstable flux tube pushes into the surrounding field thin current sheets form. If the instability displaces the flux tube upwards another current sheet forms underneath the flux tube, similar to the current sheet seen in the previous model. The reconnection process eventually starting in the current sheet below the flux tube has been linked to the often observed X-ray sigmoids (e.g. Kliem et al. 2004; Gibson et al. 2004, see Fig. 3). A deficiency of the model is that the energy storage processes, i.e. how such an unstable flux tube can be created in the first place is yet unclear. Possibilities are the emergence of twisted flux from below the photosphere or reconnection processes.

Another very promising model for large-scale energy release is the magnetic break-out model (Antiochos et al. 1999, see Fig. 4). The fundamental idea of the magnetic break-out model is that the part of the magnetic field in which the energy is stored (e.g. by photospheric shearing motions as shown in Fig. 4) is initially prevented from erupting by an overlying potential field. The continuing slow energy storage causes the initially low-lying sheared field lines to rise and to push the overlying potential field upward. In the generic break-out model (see Fig. 4), this magnetic field is embedded into a bigger structure of two neighbouring magnetic arcades and an overlying field. A magnetic null point ($\mathbf{B} = \mathbf{0}$) is located at the point where the overlying magnetic field and the field containing the sheared arcade meet. This originally potential null point is deformed by the rise of the mag-

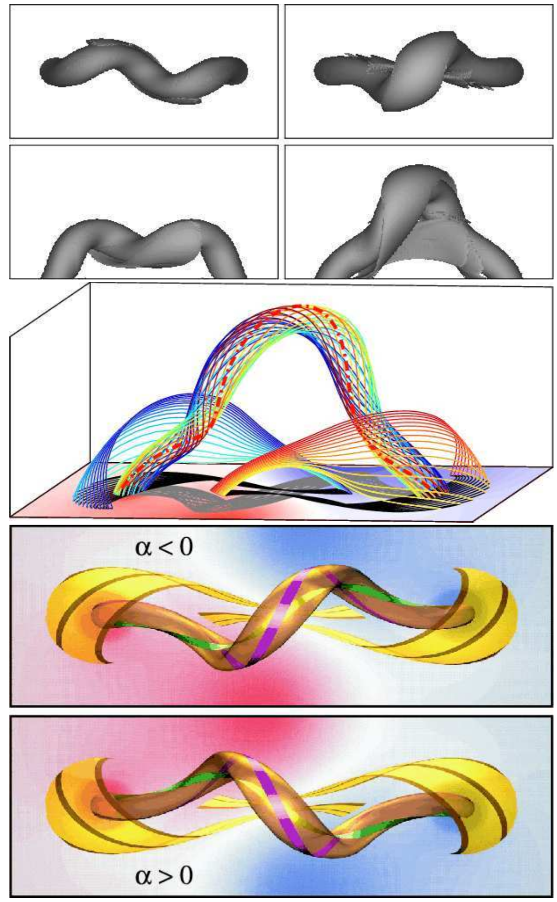

Figure 3. The three plots show different graphical representations of the kink instability model by Török et al. (2004). The model follows the nonlinear evolution of a class of kink unstable nonlinear equilibria containing a current carrying coronal loop (Titov & Démoulin 1999). The four pictures in the top panel show the current carrying loop at four different times during the evolution. The surface shown is a current isosurface. An important detail of the figure on the lower right are the additional current sheets which form around the current loop, due to the kinking magnetic field pushing into the undistorted surrounding magnetic, and underneath the rising flux tube. The middle panel shows the flux tube at a time similar to that in fourth figure of the upper panel, and another set of field lines which cross the current sheet formed underneath the rising flux tube. If magnetic reconnection occurs at the current sheet position these field lines should contain hot plasma and would show the typical sigmoidal structure often associated with solar eruptions. This is shown schematically in the lower panel for a magnetic field configurayion with $\alpha < 0$ and $\alpha > 0$. This model produces the correct hemispheric pattern of sigmoid shapes, which would not be obtained if the kinking magnetic loop is regarded as the sigmoid.

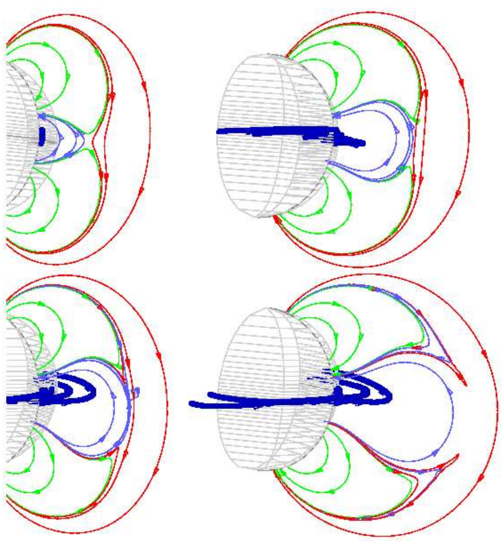

Figure 4. Magnetic field configuration of the magnetic breakout model of Antiochos et al. (1999) at four different times of the model evolution. The model has four different magnetic flux domains, three neighbrouring regions of magnetic arcades and magnetic flux overlying the three arcades. Bewteen the middle arcade and the overlying field lines a magnetic X-point exists. Energy is stored by shearing the lower lying field lines in the arcade in the middle. This causes the flux in the middle arcade to push upward and a current sheet to form at the X-point. Magnetic reconnection in the current sheet removes some of the constraining overlying flux and eventually allows the sheared field to erupt.

netic arcade beneath it and a current sheet forms, leading to reconnection between the arcade field lines and the embedding field. This reconnection process opens the field structure because it diminishes the magnetic flux confining the sheared arcade. This eventually leads to the fast break-out of the sheared structure from the system. During the fast rise and escape of the sheared magnetic field again a current sheet with ongoing magnetic reconnection is formed beneath the escaping field, similar to the current sheets formed in the models discussed above.

In the three models of large-scale energy storage and release described her, the formation of thin current sheets and magnetic reconnection within these thin current sheets plays an important role for the energy release process, and is a common feature of most models for large-scale coronal energy release. Depending on the model the current sheets form at different locations and at different times, but invariably a reconnection current sheet forms underneath the erupting structure, in line with the so-called standard model.

3. ENERGY RELEASE AND MAGNETIC TOPOLOGY AND GEOMETRY

An influence of magnetic topology on flare energy release has already been suggested a long time ago (e.g. Sweet 1958). Observations of flare emission in various wavelength bands also suggests that there is a connection between the locations of the emission and the topology of the magnetic field (see discussion below).

The fundamental building blocks of magnetic topology are magnetic null points, bald patches, separatrix surfaces and separator field lines. At magnetic null points the magnetic field vanishes ($\mathbf{B} = \mathbf{0}$). A magnetic null point defines two sets of field lines ending or starting at the null point (see Fig. 5) : the spine field lines define a single space curve through the null point, whereas the fan field lines define a surface containing the null point. Depending on the direction of spine and fan field lines we speak of positive (fan field lines point away from null point; see Fig. 5) or negative nulls (fan field lines point toward null point). For a detailed discussion of the mathematical structure of magnetic null points we refer the reader to e.g. Parnell et al. (1996). From Fig. 5 we see that in particular the fan surfaces associated with null points separate the magnetic field lines of different spatial domains, they act as separatrix surfaces.

Bald patches are locations on the lower boundary (photosphere) where the magnetic field touches the photosphere tangentially (e.g. Titov et al. 1993). Like null points these locations can determine domains of different magnetic connectivity.

The fan surfaces of a positive and a negative null point usually intersect, thus defining domains of different magnetic connectivity. The line of intersection is a magnetic field line which runs from one null point to the other null

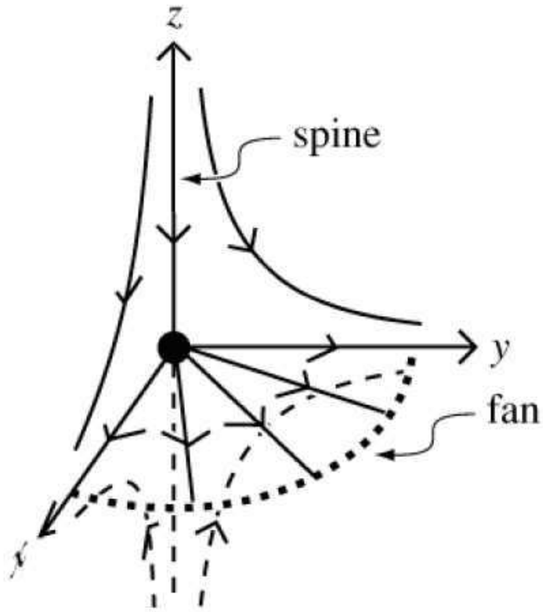

Figure 5. Field line structure of a magnetic null point.

point. This field line is called a separator field line or separator. An example is shown in Fig. 6.

Null points, bald patches, separatrix surfaces and separators are *topological* features of the magnetic field – they cannot be removed by any smooth deformation of the magnetic field. Motivated partially by observations and partially by theoretical considerations, it has been discovered over the past fifteen years that magnetic fields which are simple from a purely topological point of view (i.e. they could be smoothly deformed into a straight or similarly simple field without any topological features) can nevertheless have geometrical properties which are as favourable for coronal energy storage and release as fields with null points or bald patches.

These geometrical features of the magnetic field are based on the mapping defined by the magnetic field lines from one polarity to the opposite polarity. This mapping changes discontinuously when a separatrix surface is crossed. Quasi-separatrix layers (QSL) are then defined as those three-dimensional domains where the mapping has a large but continuous gradient (Priest & Démoulin 1995; Titov et al. 2002). The intersection of two QSLs is a hyperbolic flux tube (HFT) (see Fig. 8). HFTs are generalizations of separator field lines to topologically simple magnetic fields.

Observationally there seems to be a correlation between the lines of intersection of separatrix and quasi-separatrix surfaces with the chromosphere/photosphere and the locations of various types of radiation associated with flare activity (e.g. Demoulin et al. 1997; Metcalf et al. 2003). It has also been found in a couple of investigations using

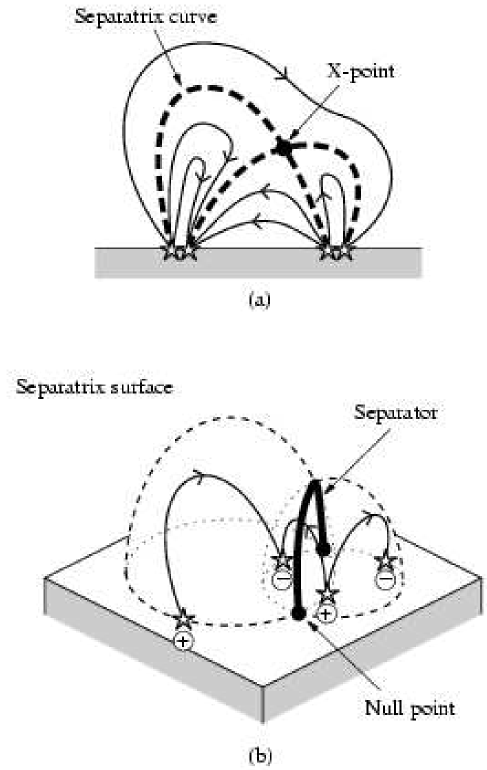

Figure 6. Typical magnetic topology created by four magnetic sources (two positive, two negative) located in the photosphere (Priest & Forbes 2002). In two dimensions (top panel) their are four different connectivity domains. The boundaries of the connectivity domains are the separatrix curves which intersect at a two-dimensional magnetic null point (X-point). In three dimensions (lower panel) two photospheric null points exist. Their fan planes are now separatrix surfaces, again defining four different domains of connectivity. Connecting the two null points is the line of intersection of the separatrix surfaces, a field line called separator field line or separator.

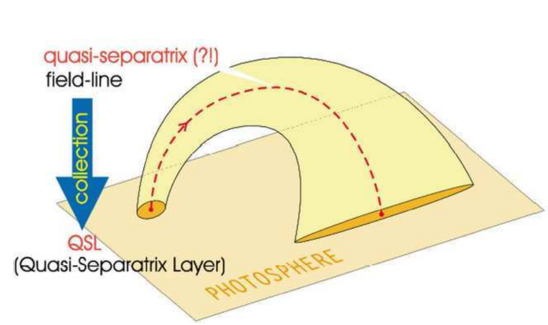

Figure 7. Inside a quasi-separatrix layer an infinitesimal flux tube is strongly distorted by the magnetic mapping from one polarity to the opposite polarity (Titov et al. 2002).

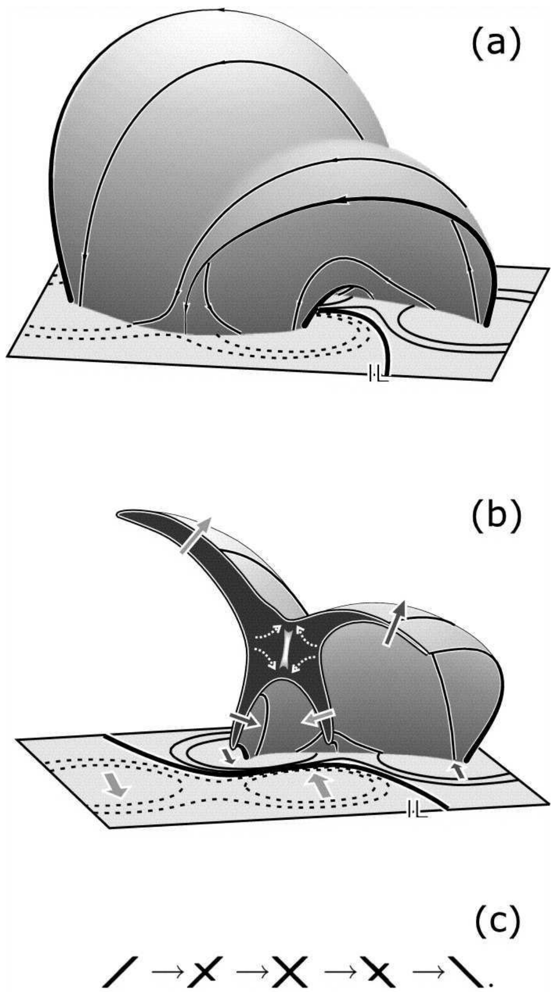

Figure 8. An example for a hyperbolic flux tube, the intersection of two quasi-separatrix layers. This example is very similar to the magnetic field structure shown in Fig. 6, but has no magnetic null points and separatrices (Titov et al. 2003; Galsgaard et al. 2003).

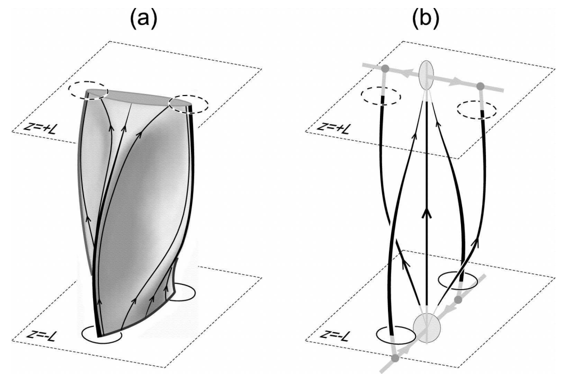

Figure 9. HFT model used for the numerical investigations. The model is a straightened out version of an HFT with two positive polarity sources on the bottom boundary and two negative polarity sources on the top boundary (Titov et al. 2003; Galsgaard et al. 2003).

magnetic field extrapolation that coronal fields associated with flaring active regions contain coronal magnetic null points (e.g Aulanier et al. 2000; Fletcher et al. 2001). The existence of a coronal magnetic null point is a key ingredient of the magnetic break-out model and Aulanier et al. (2000) suggest that their results support magnetic break-out as the mechanism operating during the flare investigated by them.

The importance of both topological and geometrical features of magnetic fields lies in the fact that they are locations where strong currents build up particularly easy. As an example we show the result of an investigation of the current build-up in a model for a HFT. The model uses a straightened version of an HFT (see Fig. 9) similar to the models used in Titov et al. (2003) and Galsgaard et al. (2003), although a slightly different initial potential magnetic field configuration is used (for details see Bocquet 2005; Bocquet et al. 2005), which is periodic in the x- and y-directions for numerical reasons.

The magnetic flux distribution through the top and bottom boundaries is changed according to specified a boundary flow. A new nonlinear force-free equilibrium is calculated for the new boundary condition. The nonlinear force-free equilibrium is calculated numerically using a magnetofrictional code. The code uses a Lagrangian mesh which deforms during the relaxation process, transporting more grid points into regions where higher numerical resolution is necessary (see Craig & Sneyd 1986, 1990; Longbottom et al. 1998). The code used here is the same as that used by Longbottom et al. (1998), but instead of a multigrid method the code uses dynamic ADI (e.g. Doss & Miller 1979) for solving the numerical equations iteratively.

Titov et al. (2003) have predicted on the basis of analytical estimations that the current build-up in the central part of HFTs is basically caused by boundary motions twisting the HFT, whereas turning motions do not have a large influence on the current build-up (Fig. 10). Of course,

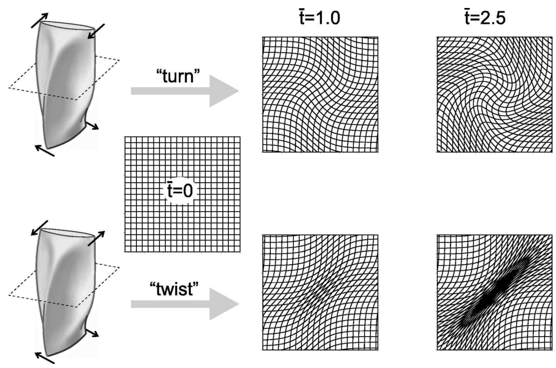

Figure 10. Prediction of the deformation by kinematic theory (Titov et al. 2003) of the central plane of an HFT under the two extreme cases of boundary motion. Strong current formation is expected in all cases in which a twisting motion is present.

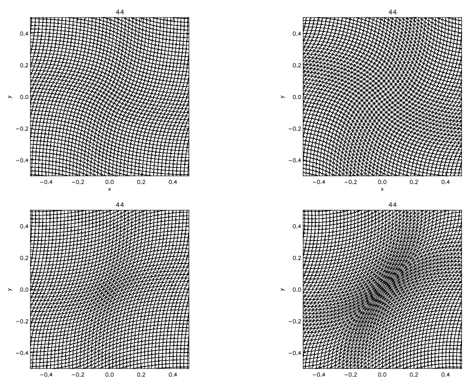

Figure 11. Example for the deformation of the Lagrangian grid in the midplane of the numerical HFT computation for the two extreme cases of turning (upper panel) and twisting (lower panel) boundary motion for two different values of footpoint displacement. The numerical results are qualitatively very similar to the analytical predictions (compare Fig. 10).

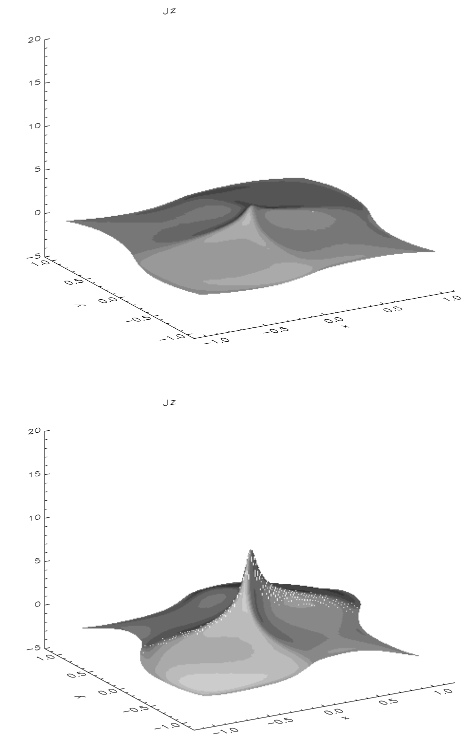

Figure 12. Example for the growth of the current concentration in the centre of an HFT, here in the extreme case of pure twisting type boundary motion. Shown are surface plots of the z-component of the current density over the Lagrangian midplane for the same values of foot point displacement used in Fig. 11. A sharp localized maximum of the current density develops surrounded by a broader domain of return current. For larger foot point displacements the maximum of the current rises exponentially, whereas the thickness of the current layer decreases. The white dots in the second plot are caused by problems of the plotting routine with the distorted grid.

such motions almost never occur in pure form on the Sun so that under generic conditions current build-up in HFTs would always have to be expected.

In Fig. 11 we show the results of two computations for pure twisting and pure turning motion. Shown is the Lagrangian grid in the (initial) midplane of an HFT configuration after boundary motion has been applied to the system. In the upper panels, the effect of a turning type boundary motion is shown, whereas in the lower panels a twisting type motion has been applied. It can be seen that the deformations of the Lagrangian grid calculated using nonlinear force-free equilibria is qualitatively similar to the predictions of the kinematic theory developed by Titov et al. (2003). The change of parameters of the HFT configuration changes the rate of deformation but not the qualitative behaviour (Bocquet 2005).

In the twisting case the deformation is much stronger and amounts to a squashing of the grid. This squashing together with the initial magnetic field structure determines the rate of growth of the current density in the centre of the HFT. In Fig. 12 we show the z-component of the current density plotted over the Lagrangian midplane of the HFT for the two values of shear already used for Fig. 11 and for twisting footpoint motion.

The growth of the z-component of the current density at the centre of the HFT with increasing foot point displacement for different magnetic field configurations is shown in Fig. 13. The main difference between the three cases shown in Fig. 13 is the thickness of the initial QSLs in the system. The solid line shows the current growth for an initially constant field containing no QSLs and HFT at all. The dotted and dashed lines show the current growth for two configurations with QSLs and HFT, where the

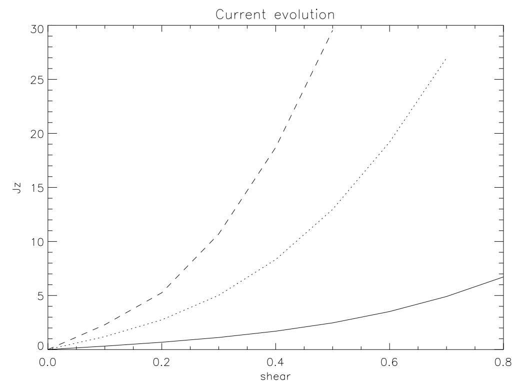

Figure 13. Plot of the increase of the maximum of the z-component of the current density in the centre of the HFT with increasing foot point displacement. The solid line shows the reference case for an initially constant magnetic field (no QSLs and no HFT). The dotted and dashed line show the strong effect of the initial QSL thickness on the increase of the current density. The dotted line corresponds to the case shown in Figs. 11 and 12. In the case of the dashed line the thickness of the QSL has been reduced by a factor of $\approx 2/3$ (measured by the squashing factor defined by Titov et al. (2002)). It is obvious that the current density increases more rapidly for thinner initial QSLs. It was also found that the current concentrations are thinner for thinner initial QSLs.

QSLs are thinner in the case of the dashed line. In general the thinner the initial QSLs and HFT, the steeper is the evolution of the current maximum. Another result is that for thinner initial QSLs the current concentration is found to be thinner.

Configurations with QSLs and HFTs are found generically in many magnetic fields of a multipolar (in particular quadrupolar) photospheric source structure. Therefore, investigations of such structures with a view to applying the theory to more realistic magnetic field configurations in the future should enable us to gain a better understanding of certain aspects of coronal energy release.

4. MAGNETIC RECONNECTION AND PARTICLE ACCELERATION

Magnetic reconnection is a physical process which is of fundamental importance for energy release in magnetized plasmas. A detailed description of the many aspects of magnetic reconnection can, for example, be found in the books by Priest & Forbes (2000) and Biskamp (2000).

Magnetic reconnection plays a part in all large-scale coronal energy release models (see Sect. 2). These models all use an MHD description, and on this level one can model the reconnection processes qualitatively by using a simple resistivity model. However, it is also clear since a long time that the normal collisional coronal resistivity is not sufficient to explain the short time scales of the eruptive processes, due to the large value of the coronal magnetic Lundquist number.

A number of suggestions have been made to overcome this problem, for example anomalous resistivity or turbulent resistivity. In numerical simulations the resistivity is usually chosen in such a way that the smallest length scales (i.e. current sheets) forming during the energy release process can still be resolved by the computational grid. A recent investigation (Birn et al. 2001) of a standard reconnection problem with a number of different codes (MHD, Hall MHD, hybrid and kinetic codes) has shown that MHD codes with scalar resistivity do not necessarily match the time evolution seen be the other codes, whereas Hall MHD seems to match the reconnection rates found by the kinetic codes reasonably well.

As we have seen in Sect. 3, the formation of strong currents on small length scales is a generic feature of complex magnetic fields evolving under nearly ideal conditions like those present in the solar corona. It is clear that during the formation of these thin current sheets the length scales involved must eventually become so small that the conditions for the validity of MHD break down locally and kinetic theory has to be used to understand the details of the dissipative processes occurring at such locations.

Apart from the general question of what the kinetic processes associated with magnetic reconnection are, there is another, related question which is particularly important for solar physics, namely : How is a large number of high energy charged particles accelerated during coronal energy release processes ? Observations indicate that a substantial amount of the released energy is transferred into high energy particles (e.g. Emslie et al. 2004). Therefore, in order to understand coronal energy release properly one has to understand the physical processes responsible for the generation of high energy particles, and how these processes are related to the large scale energy release processes occurring on the MHD scale.

Since magnetic reconnection is a common feature of all large scale energy release models it is natural to investigate first whether and how charged particles can be accelerated during magnetic reconnection. Magnetic reconnection is generically associated with parallel electric fields (e.g Hesse & Schindler 1988; Schindler et al. 1988), which are large enough to explain, at least in principle, the maximum particle energies which are observed (e.g. Schindler et al. 1991).

The state-of-the-art of theoretical investigations of particle acceleration by magnetic reconnection in solar flares is to use stationary two-dimensional X-point or current sheet fields with or without a guide field component in the invariant direction. A lot of this work is directly related to similar studies of particle acceleration in the magnetotail. As the solar corona is usually believed to be a low-β plasma, the coronal magnetic fields are assumed to be force-free. In most models this is achieved by adding a strong magnetic field component in the invariant direction (guide field) to a 2D X-point or current sheet field.

Studies of test particle orbits with X-point topologies without a guide field have been presented by e.g. Bulanov & Sasorov (1976), Vekstein & Browning (1997) and Heerikhuisen et al. (2002), whereas similar investigations including a guide field have been described by e.g. Bulanov (1980), Bruhwiler & Zweibel (1992), Mori et al. (1998) and Browning & Vekstein (2001). For laboratory applications, investigations of test particle orbits in an X-point plus guide magnetic field were also carried out by Egedal and co-workers (Egedal & Fasoli 2001a,b; Egedal et al. 2001; Egedal 2002). More recently, Dalla & Browning (2005) have studied particle acceleration in the vicinity of a three-dimensional null point, but for ideal conditions, i.e. without any parallel electric field.

Flare particle acceleration in current sheets without a guide field has been investigated by e.g. Martens (1988) and Martens & Young (1990). The influence of a guide field on the acceleration process in current sheets has been investigated by Zhu & Parks (1993), Litvinenko (1996) (see also e.g. Litvinenko & Somov 1993) and by Zharkova & Gordovskyy (2004b). Acceleration in magnetic fields with combined current sheet and X-point topology has been studied for example by Heerikhuisen et al. (2002), Craig & Litvinenko (2002), Zharkova & Gordovskyy (2004a) and Wood & Neukirch (2005).

Except for Heerikhuisen et al. (2002) (see also Craig & Litvinenko 2002) who use an exact stationary reconnective annihilation solution (with vanishing guide field) of the MHD equations found by Craig & Henton (1995), all these studies choose their magnetic field ad hoc or from purely kinematic considerations, i.e. no attempts are made to solve the MHD equations fully or approximately. This is usually justified as representing the magnetic field structure correctly in the vicinity of the nonideal region. Also, with the exception of Wood & Neukirch (2005), all authors use a spatially constant electric field in the invariant direction. This is consistent with the assumptions of stationarity and spatial invariance.

The typical procedure is then to integrate the equation of motion for charged particles in the given fields, either (semi-)analytically or numerically, and to construct the distribution function of particle energies as the particles leave the acceleration region (i.e. the vicinity of the X-point or the current sheet). This is usually done by following the method introduced by Bulanov & Sasorov (1976) who calculate the outgoing energy distribution function under the assumption of an initially uniform particle flux into the reconnection region. The resulting energy distributions usually have a power law behavior ($f(E) \sim E^{-\gamma}$) for the energy range relevant for flares. For values of the parallel electric field in the range quoted above, charged particles are relatively easily accelerated to energies observed in flares.

A general problem of this type of acceleration mechanism is that for a realistic size of the accelerating domain (i.e. the domain with nonvanishing $E_\|$) the number of particles accelerated falls way short (by several orders of magnitude) of the numbers required to explain the observed nonthermal emission (see e.g. Wood & Neukirch 2005). To solve this problem one would either have to make the acceleration region unrealistically large, for example by assuming a very extended reconnecting current sheet (Litvinenko 1996, e.g. assumes a current sheet length of 10^4 km with a width of 500 km), or to assume that a large number of small reconnection sites exists in the acceleration region which could compensate the shortage of particles from a single site.

Particle acceleration in time-dependent analytical fields has been studied e.g. by Fletcher & Petkaki (1997), Petkaki & MacKinnon (1997) and Hamilton et al. (2003). Fields taken from MHD simulations of a reconnecting current sheet have been used for example by Kliem (1994) and Kliem et al. (2000). More recently Turkmani et al. (2005) have used the fields from MHD braiding experiments for test particle calculations. In this study the particles can be accelerated in a number of acceleration sites which are distributed stochastically throughout the simulation domain. It is, however, not entirely clear how this numerical experiment is related to the general MHD picture of solar flares and more work in this direction needs to be done.

Acceleration mechanisms not directly related to the parallel electric field associated with magnetic reconnection, but with the energy of the reconnection outflow are collapsing magnetic trap models (e.g. Somov & Kosugi 1997; Kovalev & Somov 2003; Karlicky & Kosugi 2004; Giuliani et al. 2005), Fermi acceleration in turbulent reconnection outflows (e.g. Moore et al. 1995; Larosa et al. 1996), acceleration at a fast termination shock formed where the reconnection outflow encounters lower lying magnetic loops with much stronger magnetic field (e.g Tsuneta & Naito 1998) or combinations of these (e.g. Selkowitz & Blackman 2004).

Another important type of acceleration mechanism are stochastic acceleration mechanisms associated with plasma turbulence and resonant wave-particle interaction (e.g Ramaty 1979; Miller & Roberts 1995; Park & Petrosian 1995; Miller et al. 1996; Park & Petrosian 1996; Miller et al. 1997; Park et al. 1997; Lenters & Miller 1998; Liu et al. 2004; Petrosian & Liu 2004). Stochastic acceleration models can explain many of the observational features of flares. Since they can in principle operate within large volumes the number problem is not as severe as for other acceleration mechanisms and they can explain the acceleration of electrons and protons to the observed energies. One particular advantage of stochastic acceleration based on wave-particle resonance is that it can explain the preferential acceleration of particular ions. This is difficult to achieve with other acceleration mechanisms. A general assumption made either explicitly or implicitly by stochastic acceleration models is that a substantial amount of energy released on large (MHD) scales is transferred into a turbulent cascade. This energy is then in turn used to generate the high-energy particle population by stochastic acceleration. How and where the energy released on large scales is converted into plasma turbulence is at present unclear. It is worth pointing out, however, that if the fraction of the total flare energy ending up in high-energy particles is really as high as 50% the energy transfer processes involved in these scenarios have to be extremely efficient.

A general problem of test particle calculations is that they do not provide a self-consistent picture of the acceleration process. This would be justified if the generated high-energy particle population is only a small fraction of the thermal background population. Due to the large number of high-energy particles generated this is not the case for solar flares. For self-consistent calculations taking the generation of electromagnetic fields by the accelerated particle population into account kinetic simulations are required.

A number of studies of collisionless reconnection using hybrid or kinetic simulations have been undertaken in the past decade (Hesse & Winske 1994; Hesse et al. 1995; Shay et al. 1998; Shay & Drake 1998; Kuznetsova et al. 2000; Rogers et al. 2001; Hesse et al. 2001a,b; Pritchett 2001b,a; Hesse et al. 2002; Zeiler et al. 2002; Hesse et al. 2004; Pritchett & Coroniti 2004; Ricci et al. 2004; Silin & Büchner 2005, e.g.), mainly for high β plasma within the reconnection region, with a view to model magnetic reconnection in the Earth's magnetotail. The typical magnetic field configuration used in these studies is that of the one-dimensional Harris sheet (Harris 1962). In some cases a constant guide field is added to the Harris sheet to mimic a situation with a lower β and to introduce currents along the initial magnetic field. Most studies focus on details of the reconnection region, but there are a few which try to apply the simulation results to the problem of particle acceleration (e.g Hoshino et al. 2001; Ricci et al. 2003; Drake et al. 2005). So far, however, no clear picture has emerged which would connect the kinetic theory of reconnection and the number problem of solar flare particle acceleration. One problem is to overcome the huge gap between the kinetic scales (a few meters to kilometers) and the MHD scales (order 10^4 km). Certainly, more work has to be done in this area before definitive statements can be made on the basis of kinetic simulations which are directly relevant for the problem of coronal energy release and particle acceleration.

5. SUMMARY AND DISCUSSION

The solar corona is a highly active and dynamic plasma-magnetic field system. Activity can be observed on virtually all length and time scales which are accessible to us. The solar magnetic field plays a fundamental role in the physical processes responsible for coronal activity. It stores the energy transferred from the motions of the much denser photospheric and sub-photospheric plasma into the corona, which is then released in large and small eruptions if certain conditions are fulfilled. The exact nature of these conditions is still a matter of active research, and a number of different models have been proposed. More work, both observational and theoretical, will be necessary to identify those models which describe the coronal energy release processes correctly.

The topological and geometrical structure of the coronal magnetic field can lead to the formation of strong current concentrations in special locations, i.e. separatrix surfaces and separator field lines, and quasi-separatrix layers and hyperbolic flux tubes. Regions of strongly localised currents are the preferred regions where the nearly ideal conditions of the corona break down and magnetic reconnection can occur.

Magnetic reconnection is a fundamental process in coronal energy release. Magnetic reconnection is part of all models of large-scale coronal energy release. It is also thought to be important for the physical processes responsible for the acceleration of a large number of charged particles to high energies during coronal energy release, in particular in flares. The exact nature of the role played by reconnection for particle acceleration is still unclear.

ACKNOWLEDGMENTS

I would like to thank François-Xavier Bocquet, Lyndsay Fletcher, Klaus Galsgaard, Paolo Giuliani, Bernhard Kliem, Slava Titov, Tibor Török and Paul Wood for sharing with me their knowledge on the various aspects of coronal energy release presented here.

REFERENCES

Amari, T., Luciani, J. F., Aly, J. J., Mikic, Z., & Linker, J. 2003, ApJ, 585, 1073

Antiochos, S. K., DeVore, C. R., & Klimchuk, J. A. 1999, ApJ, 510, 485

Aulanier, G., DeLuca, E. E., Antiochos, S. K., McMullen, R. A., & Golub, L. 2000, ApJ, 540, 1126

Baty, H. 1997, A&A, 318, 621

Baty, H., Einaudi, G., Lionello, R., & Velli, M. 1998, A&A, 333, 313

Birn, J., Drake, J. F., Shay, M. A., et al. 2001, J. Geophys. Res., 106, 3715

Biskamp, D. 2000, Magnetic Reconnection in Plasmas (Cambridge, England: Cambridge University Press)

Bocquet, F.-X. 2005, PhD thesis, University of St. Andrews

Bocquet, F.-X., Neukirch, T., Titov, V. S., & Galsgaard, K. 2005, ApJ, in preparation

Browning, P. & Vekstein, G. 2001, Journal of Geophys. Res., 106, 18,677

Bruhwiler, D. & Zweibel, E. 1992, Journal of Geophys. Res., 97, 10,825

Bulanov, S. V. 1980, Soviet Astronomy Letters, 6, 206

Bulanov, S. V. & Sasorov, P. V. 1976, Soviet Astronomy, 52, 763

Craig, I. J. D. & Henton, S. M. 1995, Astrophys. Journal, 450, 280

Craig, I. J. D. & Litvinenko, Y. E. 2002, Astrophys. Journal, 570, 387

Craig, I. J. D. & Sneyd, A. D. 1986, ApJ, 311, 451

Craig, I. J. D. & Sneyd, A. D. 1990, ApJ, 357, 653

Dalla, S. & Browning, P. K. 2005, A&A, 436, 1103

Demoulin, P., Bagala, L. G., Mandrini, C. H., Henoux, J. C., & Rovira, M. G. 1997, A&A, 325, 305

Doss, S. & Miller, K. 1979, SIAM J. Numer. Anal., 16, 837

Drake, J. F., Shay, M. A., Thongthai, W., & Swisdak, M. 2005, Physical Review Letters, 94, 095001

Egedal, J. 2002, Phys. Plasmas, 9, 1095

Egedal, J. & Fasoli, A. 2001a, Phys. Rev. Letters, 86, 5047

Egedal, J. & Fasoli, A. 2001b, Phys. Plasmas, 8, 4042

Egedal, J., Fasoli, A., Tarkowski, D., & Scarabosio, A. 2001, Phys. Plasmas, 8, 1935

Emslie, A. G., Kucharek, H., Dennis, B. R., et al. 2004, Journal of Geophysical Research (Space Physics), 109, 10104

Fan, Y. 2005, ApJ, 630, 543

Fletcher, L., Metcalf, T. R., Alexander, D., Brown, D. S., & Ryder, L. A. 2001, ApJ, 554, 451

Fletcher, L. & Petkaki, P. 1997, Solar Phys., 172, 267

Forbes, T. G. 1991, Geophysical and Astrophysical Fluid Dynamics, 62, 16

Forbes, T. G. 2000, J. Geophys. Res., 105, 23153

Forbes, T. G. & Priest, E. R. 1995, ApJ, 446, 377

Galsgaard, K., Titov, V. S., & Neukirch, T. 2003, ApJ, 595, 506

Gerrard, C. L., Arber, T. D., Hood, A. W., & Van der Linden, R. A. M. 2001, A&A, 373, 1089

Gibson, S. E., Fan, Y., Mandrini, C., Fisher, G., & Demoulin, P. 2004, ApJ, 617, 600

Giuliani, P., Neukirch, T., & Wood, P. 2005, ApJ, accepted

Hamilton, B., McClements, K. G., Fletcher, L., & Thyagaraja, A. 2003, Solar Phys., 214, 339

Harris, E. G. 1962, Nuovo Cimento, 23, 115

Heerikhuisen, J., Litvinenko, Y. E., & Craig, I. J. D. 2002, Astrophys. Journal, 566, 512

Hesse, M., Birn, J., & Kuznetsova, M. 2001a, J. Geophys. Res., 106, 3721

Hesse, M., Kuznetsova, M., & Birn, J. 2001b, J. Geophys. Res., 106, 29831

Hesse, M., Kuznetsova, M., & Birn, J. 2004, Physics of Plasmas, 11, 5387

Hesse, M., Kuznetsova, M., & Hoshino, M. 2002, Geophys. Res. Lett., 29, 4

Hesse, M. & Schindler, K. 1988, Journal of Geophys. Res., 93, 5559

Hesse, M. & Winske, D. 1994, J. Geophys. Res., 99, 11177

Hesse, M., Winske, D., & Kuznetsova, M. M. 1995, J. Geophys. Res., 100, 21815

Hood, A. W. & Priest, E. R. 1979, Sol. Phys., 64, 303

Hoshino, M., Mukai, T., Terasawa, T., & Shinohara, I. 2001, J. Geophys. Res., 106, 25979

Karlicky, M. & Kosugi, T. 2004, Astron. Astrophys., 419, 1159

Kliem, B. 1994, Astrophys. Journal, 90, 719

Kliem, B., Karlický, & Benz, A. O. 2000, Astron. Astrophys., 360, 715

Kliem, B., Titov, V. S., & Török, T. 2004, A&A, 413, L23

Kovalev, V. A. & Somov, B. V. 2003, Astronomy Letters, 29, 409

Kuznetsova, M. M., Hesse, M., & Winske, D. 2000, J. Geophys. Res., 105, 7601

Larosa, T. N., Moore, R. L., Miller, J. A., & Shore, S. N. 1996, Astrophys. Journal, 467, 454

Lenters, G. T. & Miller, J. A. 1998, Astrophys. Journal, 493, 451

Lin, J., Soon, W., & Baliunas, S. L. 2003, New Astronomy Review, 47, 53

Litvinenko, Y. 1996, Astrophys. Journal, 462, 997

Litvinenko, Y. & Somov, B. 1993, Solar Phys., 146, 127

Liu, S., Petrosian, V., & Mason, G. M. 2004, Astrophys. Journal, 613, L81

Longbottom, A. W., Rickard, G. J., Craig, I. J. D., & Sneyd, A. D. 1998, ApJ, 500, 471

Martens, P. 1988, Astrophys. Journal, 330, L131

Martens, P. C. H. & Young, A. 1990, Astrophys. Journal Suppl. Ser., 73, 333

Metcalf, T. R., Alexander, D., Hudson, H. S., & Longcope, D. W. 2003, Astrophys. Journal, 595, 483

Miller, J., Cargill, P., Emslie, A., et al. 1997, Journal of Geophys. Res., 102, 14,631

Miller, J., LaRosa, T., & Moore, R. 1996, Astrophys. Journal, 461, 445

Miller, J. & Roberts, D. 1995, Astrophys. Journal, 452, 912

Moore, R. L., Larosa, T. N., & Orwig, L. E. 1995, Astrophys. Journal, 438, 985

Mori, K., Sakai, J., & Zhao, J. 1998, Astrophys. Journal, 494, 430

Park, B. T. & Petrosian, V. 1995, Astrophys. Journal, 446, 699

Park, B. T. & Petrosian, V. 1996, Astrophys. Journal Suppl. Ser., 103, 255

Park, B. T., Petrosian, V., & Schwartz, R. A. 1997, Astrophys. Journal, 489, 358

Parnell, C. E., Smith, J. M., Neukirch, T., & Priest, E. R. 1996, Physics of Plasmas, 3, 759

Petkaki, P. & MacKinnon, A. L. 1997, Solar Phys., 172, 279

Petrosian, V. & Liu, S. 2004, Astrophys. Journal, 610, 550

Priest, E. & Forbes, T. 2000, Magnetic Reconnection (Cambridge, England: Cambridge University Press)

Priest, E. R. & Démoulin, P. 1995, J. Geophys. Res., 100, 23443

Priest, E. R. & Forbes, T. G. 2002, A&A Rev., 10, 313

Pritchett, P. L. 2001a, J. Geophys. Res., 106, 25961

Pritchett, P. L. 2001b, J. Geophys. Res., 106, 3783

Pritchett, P. L. & Coroniti, F. V. 2004, Journal of Geophysical Research (Space Physics), 109, 1220

Ramaty, R. 1979, in AIP Conf. Proc. 56: Particle Acceleration Mechanisms in Astrophysics, 135–154

Ricci, P., Brackbill, J. U., Daughton, W., & Lapenta, G. 2004, Physics of Plasmas, 11, 4102

Ricci, P., Lapenta, G., & Brackbill, J. U. 2003, Physics of Plasmas, 10, 3554

Rogers, B. N., Denton, R. E., Drake, J. F., & Shay, M. A. 2001, Physical Review Letters, 87, 195004

Schindler, K., Hesse, M., & Birn, J. 1988, Journal of Geophys. Res., 93, 5547

Schindler, K., Hesse, M., & Birn, J. 1991, Astrophys. Journal, 380, 293

Selkowitz, R. & Blackman, E. G. 2004, Mon. Not. Roy. Astron. Soc., 354, 870

Shay, M. A. & Drake, J. F. 1998, Geophys. Res. Lett., 25, 3759

Shay, M. A., Drake, J. F., Denton, R. E., & Biskamp, D. 1998, J. Geophys. Res., 103, 9165

Silin, I. & Büchner, J. 2005, Physics of Plasmas, 12, 2320

Somov, B. & Kosugi, T. 1997, Astrophys. Journal, 485, 859

Sweet, P. A. 1958, in IAU Symp. 6: Electromagnetic Phenomena in Cosmical Physics, 123–134

Titov, V. S. & Démoulin, P. 1999, A&A, 351, 707

Titov, V. S., Galsgaard, K., & Neukirch, T. 2003, ApJ, 582, 1172

Titov, V. S., Hornig, G., & Démoulin, P. 2002, Journal of Geophysical Research (Space Physics), 107, 3

Titov, V. S., Priest, E. R., & Demoulin, P. 1993, A&A, 276, 564

Török, T., Kliem, B., & Titov, V. S. 2004, A&A, 413, L27

Tsuneta, S. & Naito, T. 1998, Astrophys. Journal, 495, L67

Turkmani, R., Vlahos, L., Galsgaard, K., Cargill, P. J., & Isliker, H. 2005, Astrophys. Journal, 620, L59

Vekstein, G. & Browning, P. K. 1997, Phys. Plasmas, 4, 2261

Wood, P. D. & Neukirch, T. 2005, Solar Phys., 226, 73

Zeiler, A., Biskamp, D., Drake, J. F., et al. 2002, Journal of Geophysical Research (Space Physics), 107, 6

Zharkova, V. V. & Gordovskyy, M. 2004a, Mon. Not. Roy. Astron. Soc., 356, 1107

Zharkova, V. V. & Gordovskyy, M. 2004b, Astrophys. Journal, 604, 884

Zhu, Z. & Parks, G. 1993, Journal of Geophys. Res., 98, 7603