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# Notes on Magnetohydrodynamics of Magnetic Reconnection in Turbulent Media

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**Abstract** Astrophysical fluids have very large Reynolds numbers and therefore turbulence is their natural state. Magnetic reconnection is an important process in many astrophysical plasmas, which allows restructuring of magnetic fields and conversion of stored magnetic energy into heat and kinetic energy. Turbulence is known to dramatically change different transport processes and therefore it is not unexpected that turbulence can alter the dynamics of magnetic field lines within the reconnection process. We shall review the interaction between turbulence and reconnection at different scales, showing how a state of turbulent reconnection is natural in astrophysical plasmas, with implications for a range of phenomena across astrophysics. We consider the process of magnetic reconnection that is fast in magnetohydrodynamic (MHD) limit and discuss how turbulence—both externally driven and generated in the reconnecting system—can make reconnection independent on the microphysical properties of plasmas. We will also show how relaxation theory can be used to calculate the energy dissipated in turbulent reconnecting fields. As well as heating the plasma, the energy dissipated by turbulent reconnection may cause acceleration of non-thermal particles, which is briefly discussed here.

**Keywords** Magnetic reconnection · Turbulence · Magnetohydrodynamics · Cosmic plasma · Fast reconnection · Solar flares · Dynamos

## 1 Introduction

Magnetic fields are observed in many astrophysical objects and it is accepted that these fields play an essential role in the dynamics (e.g. Crutcher 1999; Beck 2002; Vallée 1997, 1998). Magnetic fields are vital for magneto-rotational instability, transport and acceleration of cosmic rays and other energetic particles, accretion of matter, and activity in stellar atmospheres

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(e.g. Balbus and Hawley 1998; Parker 1992; Schlickeiser and Lerche 1985; Melrose 2009; Elmegreen and Scalo 2004; Kotera and Olinto 2011). Crucially, magnetic fields provide a means to store energy as well as to transport it.

For laminar fluids in the limit of zero resistivity, the topology of the field lines is a constant of motion and the magnetic flux threading any fluid element is constant. This is the basis of the textbook notion that in the limit of very small resistivity, which is typical for astrophysical objects, the magnetic flux is "frozen in" and magnetic field lines resist passing through one another or changing their topology (Moffat 1978).[1]

At the same time, changes of magnetic field topology are necessary for the generation of magnetic fields by dynamos, and for many other phenomena. Magnetic reconnection is a process that is responsible for topology changes and the annihilation of magnetic field on faster time-scales than the (usually) extremely slow, process of global resistive diffusion. It is now well-established that magnetic reconnection is a ubiquitous process across the universe, with important consequences for restructuring of magnetic fields and efficient release of stored magnetic energy, such as in solar and stellar flares, coronal heating and planetary magnetospheres; for reviews, see Biskamp (1996, 2000), Priest and Forbes (2000), Yamada (2007), Zweibel and Yamada (2009), Yamada et al. (2011). Furthermore, reconnection is common in laboratory plasmas, both in magnetically-confined fusion devices (e.g. Ono et al. 2012; Stanier et al. 2013) and in experiments specifically devised to study reconnection (e.g. Yamada et al. 1990; Brown 1999; Yamada 2007). Whilst reconnection theory originated mainly through 2D analytical models (Parker 1957; Sweet 1958; Furth et al. 1963; Petschek 1964; Hahm and Kulsrud 1985), recent research on astrophysical reconnection has increasingly emphasised the role of 3D geometries and complex topologies. One strand of such complexity is a close association between magnetic reconnection and turbulence, which is the focus of this paper.

Turbulence is an almost universal process in astrophysical plasmas; as well as being widely observed in laboratory plasmas, and associated there with the important and yet ill-understood phenomenon of anomalous transport. For instance, in the interstellar medium, supernovae explosions are thought to be the source of ubiquitously observed turbulent motions. It is generally accepted that the "Big Power Law in the Sky" (see Fig. 1) indicates the presence of turbulence on scales from tens of parsecs to thousands of kilometres (Armstrong et al. 1995; Chepurnov and Lazarian 2010). Among other sources, evidence for this comes from studies of atomic hydrogen spectra in molecular clouds and galaxies (Lazarian and Pogosyan 1999; Stanimirović and Lazarian 2001; Padoan et al. 2006, 2009; Chepurnov et al. 2010), see also the review by Lazarian (2009) and references therein; as well as recent studies of emission lines and Faraday rotation (see Burkhart et al. 2010; Gaensler et al. 2011). Much work over recent years has been devoted to understanding fluid turbulence in the presence of a magnetic field (e.g. Zank and Matthaeus 1993; Lazarian and Cho 2005).

In fact, the phenomena of reconnection and turbulence in magnetised plasmas, traditionally viewed as separate problems, should be studied together. This is inevitably a vast subject, and in this review we touch only on some aspects of this, focussing only on magnetohydrodynamic (MHD) models. Recently, there has also been much emphasis on the interaction between turbulence and reconnection in collisionless reconnection (e.g. Daughton et al. 2011; Karimabadi et al. 2013) and Hall-MHD (e.g. Dmitruk and Matthaeus 2006), but here we consider only fluid models. The many interesting recent developments in kinetic models of turbulence and reconnection are discussed elsewhere in this volume. The interaction between turbulence and reconnection within MHD are also reviewed by Lazarian et al.

[1] As we discuss later in Sect. 3.4, the very notion of frozen-in magnetic fields requires serious revisions.

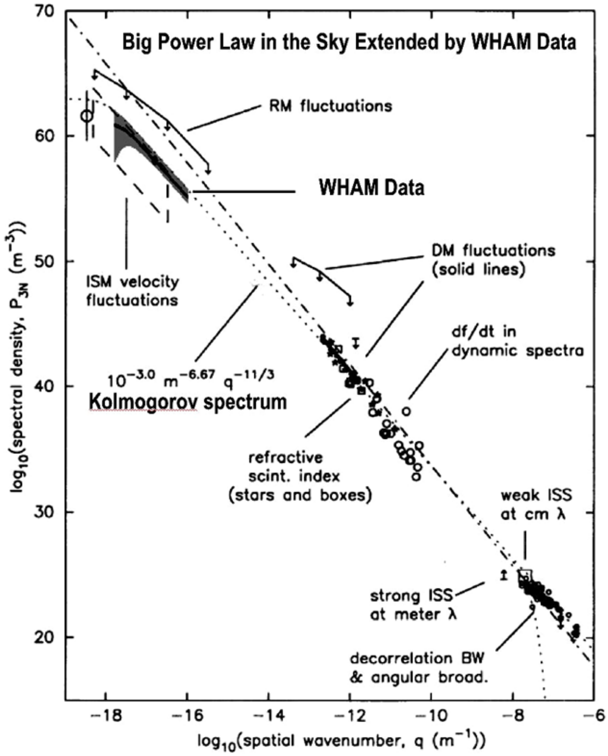


**Fig. 1** Turbulence in the interstellar gas as revealed by electron density fluctuations. "Big Power Law in the Sky" in extended using WHAM data (Armstrong et al. 1995). The slope corresponds to that of Kolmogorov turbulence (see discussion in Armstrong et al. (1995)). Modified from Chepurnov and Lazarian (2010)

(2012b), focused more on a review of MHD turbulence (which is not covered here) and on cosmic ray acceleration. A complementary review is provided by Servidio et al. (2011), considering the role of reconnecting current sheets within 2D turbulence, in both MHD and Hall-MHD frameworks.

Reconnection and turbulence may interact in a number of ways. Firstly, a realisation that flows are turbulent on fluid scales can substantially modify the dynamics of reconnection and lead to *fast reconnection*, as described in the following section and Sect. 3. Secondly, turbulence on kinetic scales is also ubiquitous, and these microphysical processes interact strongly with the global (fluid scale) dynamics (e.g. Karimabadi et al. 2013). Whilst discussion of kinetic processes is beyond the scope of this paper, we discuss synergies between the MHD and plasma-based approaches to reconnection in Sect. 4, and some effects of microphysics on fluid processes are mentioned in Sect. 5. Thirdly, within a single reconnecting current sheet, there is natural tendency for fragmentation into a series of plasmoids, leading again to a turbulent scenario, as discussed briefly in Sect. 5. Fourthly, the dynamics of a magnetised plasma involving instabilities and loss of equilibrium naturally lead to fine structure and turbulence, as is discussed in Sect. 6.1—thus reconnection tends to occur in a multiplicity of localised current sheets (or similar structures), with turbulence naturally arising. Reconnection in such complex fields is usually 3D rather than 2D, see Sect. 6.2. Finally, an important consequence of turbulent reconnection in cosmic plasmas is the efficient dissipation of stored magnetic energy—leading both to plasma heating and the energisation of charged particles. An approach to the former, based on the idea of relaxation to a minimum energy state, is outlined in Sect. 7, whilst the latter is reviewed in Sect. 8.

## 2 "Classical" Reconnection Models and the Quest for Fast Reconnection

The first analytic model for magnetic reconnection was proposed independently by Parker (1957) and Sweet (1958). *Sweet-Parker reconnection* has the virtue that it relies on a robust and straightforward geometry. Two regions with uniform magnetic fields are separated by thin current sheet. The speed of reconnection is given roughly by the resistivity divided by the sheet thickness, i.e. $V_{rec} \approx \eta/\Delta$, where $\eta$ is the resistivity. This suggests that the reconnection can be very fast for small $\Delta$ and by decreasing $\Delta$, one can make reconnection as fast as may be required. This is not true, however. Indeed, the conducting plasma in the current sheet is constrained to move along the local field lines, and is ejected from the edge of the current sheet at the Alfvén speed, $V_A$. Since the width of the current sheet, $\Delta$, limits the flux of expelled fluid, $\Delta$ should be made as large as possible to enable faster reconnection. This results, for steady-state reconnection, in a compromise, with the overall reconnection speed reduced from the Alfvén speed by the square root of the Lundquist number, $S \equiv LV_A/\eta$, where $L$ is the length of the current sheet. In most astrophysical contexts, $S$ is very large and the Sweet-Parker reconnection speed, $V_{SP} \approx V_A S^{-1/2}$, is very small. Fast reconnection requires that the reconnection rate be independent of $\eta$ or depend on $S$ logarithmically.

Another early paradigm for reconnection, which treats the transient development of reconnection rather than assuming a steady-state, is the *tearing instability* (Furth et al. 1963). A magnetic field with a reversal—or more generally, a sheared field—may be linearly-unstable to small perturbations, forming a chain of growing magnetic islands at the reversal surface (or resonant surface, where $\mathbf{k} \cdot \mathbf{B} = 0$). However, the growth rate scales with the geometric mean of the Alfven and diffusive times, which again is too slow to explain phenomena such as solar flares.

A further analytical model for reconnection is *forced reconnection* (Hahm and Kulsrud 1985), in which an external disturbance at the boundary triggers reconnection and energy-release, in a field which may be tearing-mode stable. In the original model, a sinusoidal disturbance is applied at the boundary of a field-reversal in a slab, leading initially to the formation of a discontinuous current sheet which subsequently relaxes through reconnection into a lower-energy state with a chain of magnetic islands. This model can be generalised to a sheared force-free field (Vekstein and Jain 1998), with implications for solar coronal heating. However, again the time-scale for energy-release is slow.

The realization that Sweet-Parker reconnection—and related time-dependent models such a linear tearing mode—are inadequate to explain magnetic reconnection for solar flares was immediately apparent, and this gave rise to much research on models of fast reconnection—see reviews Biskamp (2000), Priest and Forbes (2000)—that used different outflow conditions, avoiding the contradictory requirements on $\Delta$ of the Sweet-Parker model. The first proposal was to replace the long current sheet with an X-point configuration, so that the "sheet" thickness and length are comparable. The magnetic field lines diverge from the "point" of reconnection, forming an X-type structure over the scale of the system. This is the basis for the ingenious Petschek's model of fast reconnection (Petschek 1964). The stability and the conditions for emergence of such structures were an issue for extensive research over the years that followed.

It is easy to see that self-consistent X-point reconnection requires that the outflow prevents a general collapse into a narrow current sheet. Otherwise we would expect that the same bulk forces that brought the magnetic field lines together would lead to Sweet-Parker reconnection, which corresponds to the collapse of the X-point to an extended Y-sheet. Petschek (1964) proposed that slow-mode shocks on either side of the X-point would serve this purpose. Moreover, these shocks are responsible for converting most of the magnetic energy into kinetic energy. The X-point in this model has an overall size which depends on resistivity, but since the magnetic field decreases logarithmically when approaching the current sheet (due to the assumption of the current-free magnetic field in the inflow region), the resulting reconnection speed depends on $\ln S$ and can be an appreciable fraction of $V_A$. Numerical simulations with uniform resistivity (Biskamp 1996) have showed that in the MHD limit, the shocks fade away and the contact region evolves into Sweet-Parker reconnection. The suggested way to make the Petschek configuration stable was by introducing a local non-uniform resistivity (Parker 1973; Ugai and Tsuda 1977; Scholer 1989; Ugai 1992; Yan et al. 1992; Forbes 2001; Shibata and Magara 2011), which remained the favourite way of accounting for fast reconnection for many years.

Plasma effects, such as anomalous resistivity (resistivity that depends on the current), formally present the best bet for stabilising the reconnecting X-point and attaining Petschek reconnection: see Sect. 5. However, there were several important issues that remained unresolved. First, it is not clear that this kind of fast reconnection persists on scales greater than the ion inertial scale (see Bhattacharjee et al. 2003). Several numerical studies (Wang et al. 2001; Smith et al. 2004; Fitzpatrick 2004) have found large-scale reconnection speeds which depend on resistivity: hence, these are not true "fast reconnection". Second, in many circumstances the magnetic field geometry does not allow the formation of X-point reconnection. For example, a saddle-shaped current sheet—the generic configuration of fluxes pressing against each other when one flux tube partially engulfs the other as they pulled in opposite directions—cannot be spontaneously replaced by an X-point. The energy required to do so is comparable to the magnetic energy liberated by reconnection, and must be available beforehand. Finally, the requirement that reconnection occurs only in collisionless plasmas is very restrictive. Many astrophysical fluids are collisional. For example, while reconnection in stellar coronae can be collisionless (at least, on the "dissipation" length-scale), stellar chromospheres are collisional. Magnetic reconnection does happen in both regions.[2] Different phases of the interstellar medium are also collisional and, while magnetic reconnection is more difficult to observe in those environments, there is an indirect way to infer fast magnetic reconnection there (Lazarian et al. 2012b).

As an example, we mention that Yamada (2007) estimated that the scale of the reconnecting current sheet should not exceed about 40 times the electron mean-free-path. This condition is not satisfied in many environments, e.g. the InterStellar Medium (ISM). The conclusion that stellar interiors and atmospheres, accretion disks, and the ISM does not allow fast reconnection is drastic and unpalatable. On the other hand, an intriguing possibility is that in some environments, such as the solar corona, a local collisionless state may be maintained, allowing fast reconnection (Uzdensky 2007).

Is there a way to make magnetic reconnection independent of resistivity within the MHD framework? Turbulence may be the primary suspect, as most of astrophysical environments are observed to be turbulent, as discussed in Sect. 1. We now discuss how turbulence may resolve the fast reconnection problem.

## 3 The Role of Turbulence in Fast Reconnection

Turbulence is known to accelerate diffusion processes, making them independent of the microphysical parameters. This reasoning was behind the ill-founded concept of turbulent

[2] In some of these environments, collisions with neutral gas may dominate over Coulomb collisions, strongly affecting the reconnection process, so the distinction between "collisionless" and "collisional" may be an over-simplification. We do not discuss this interesting issue further here.

diffusivity within models of the kinematic dynamo (Moffat 1978). There, in direct analogy with the turbulent diffusivity of a passive scalar, it was assumed that magnetic fields can be mixed by turbulent motions up to the resistive scale. Naturally, in such circumstances, the magnetic reconnection problem becomes trivial.

The problem with the "magnetic turbulent diffusion" idea is that realistic astrophysical magnetic fields are important and therefore the small-scale magnetic mixing of oppositely-directed magnetic fields is not applicable. In fact, the dynamical importance of magnetic fields and the inability of the turbulence to bend them appreciably on the resistive scales must be taken into account from the very early stages of the action of astrophysical dynamo.

Thus, in addressing the role of turbulence in astrophysical reconnection, one should consider dynamically important magnetic fields. Lazarian and Vishniac (1999) [hereafter LV99] proposed a 3D model for fast reconnection which depends on the presence of turbulence, and magnetic field wandering.

We must note that the idea that turbulence and fieldline wandering can enhance the reconnection rate has a long history. For instance, Speiser (1970) considered the effects of turbulence on microscopic resistivity—further discussed in Sect. 5. The "Tangled Discharge Model" was devised to explain relaxation in a Reversed Field Pinch and other fusion devices through the existence of stochastic fields subject to turbulent reconnection (Rusbridge 1977, 1991). Similarly, Jacobson and Moses (1984) proposed that the current diffusivity should be modified to include the diffusion of electrons across the large scale magnetic field due to the small-scale field line stochasticity. These models involving field line wandering are also closely linked to the idea of relaxation to a minimum energy state, see Sect. 7 below, and provide a very useful picture of the interactions between turbulence and reconnection; but they do not solve the fast reconnection problem. Further models considering the effects of 2D turbulence on reconnection are discussed in Sect. 3.3 below. We now proceed to show how 3D fluid turbulence may provide a solution to the fast reconnection problem.

### 3.1 The LV99 Model

LV99's model (see Fig. 2) uses the properties of turbulence to predict broad outflows from extended current sheets. The diffusivity of magnetic field line trajectories in a turbulent plasma implies that flows can follow local magnetic field lines without being confined to the current sheet. When the turbulent diffusivity is less than the ohmic resistivity, this model reduces to the Sweet-Parker reconnection model.

Let us consider the differences between the Sweet-Parker model of laminar reconnection (Sect. 2) and LV99 which accounts for turbulence. The latter can be seen as a generalization of the Sweet-Parker model (see Fig. 2) in the sense that the two regions of differing magnetic directions are pressed up against one another over a broad contact region. This is a generic configuration, which should arise naturally whenever a magnetic field has a non-trivial configuration, whose energy could be lowered through reconnection. The outflow of plasma and reconnected flux will fluctuate as the turbulence evolves and the field line connections change, but the long term average will reflect the turbulent diffusion of the field lines. Consequently, the essential difference between the Sweet-Parker model and the LV99 model is that in the former, the outflow is limited by microphysical Ohmic diffusivity; while in LV99, the large-scale magnetic field wandering determines the thickness of outflow. The latter depends only on the turbulence properties and is independent of resistivity. This ensures that the LV99 reconnection is fast.

For extremely weak turbulence, when the value of $\Delta$ arising from magnetic field wandering becomes smaller than the width of the Sweet-Parker layer $LS^{-1/2}$, the two models

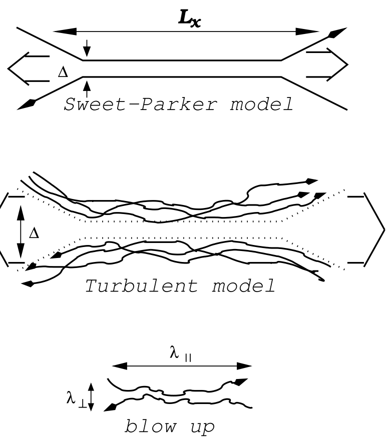


**Fig. 2** *Upper plot*: The Sweet-Parker reconnection model. The outflow is confined to a thin layer of width $\Delta$, which is set by Ohmic diffusivity. The length of the current sheet is a macroscopic scale $L \gg \Delta$. Magnetic field lines are assumed to be laminar. *Middle plot*: Reconnection in the presence of stochastic magnetic field lines. The stochasticity introduced by turbulence is weak and the mean field provides a clear direction. The outflow width is set by the diffusion of the magnetic field lines, which is a macroscopic process, independent of resistivity. *Lower plot*: An individual small-scale reconnection region. The reconnection over small patches of magnetic field determines the local reconnection rate. The global reconnection rate is substantially larger as many independent patches reconnect simultaneously. Conservatively, the LV99 model assumes that the small scale events happen at a slow Sweet-Parker rate. From Lazarian et al. (2004)

are indistinguishable and the reconnection proceeds at the Sweet-Parker rate. Similarly, we expect that when the turbulence-induced $\Delta$ is much larger than the Larmor radius of ions, then the plasma effects should not be important.

With the Goldreich and Sridhar (1995) model of turbulence, LV99 obtained:

$$V_{rec} = V_A \left(\frac{l}{L}\right)^{1/2} \left(\frac{v_l}{V_A}\right)^2, \qquad (1)$$

where $l$ and $v_l$ are the energy injection scale and velocity at the injection scale, respectively. This expression assumes that energy is injected isotropically at a scale $l$ smaller than the length of the current sheet $L$, which for sub-Alfvénic turbulence leads to the generation of weakly-interacting waves at that scale. The waves transfer energy to modes with larger values of $k_\perp$ until at a scale $l_{trans} = LM_A^2$, where $M_A$ is the Alfven Mach number, strong turbulence sets in Lazarian (2006). It is important to note that the strongly turbulent eddies have a characteristic velocity of $v_{turb} \approx V_A(v_l/V_A)^2$. In other words, the reconnection speed is the large-eddy, strong-turbulent velocity multiplied factors which depend on whether the current sheet length is smaller or larger than the large eddies (whose length is approximately the injection scale). In this sense, the reconnection speed is insensitive to the exact mechanism for turbulent power injection.

It is important to note three features of Eq. (1). First, and most important, it is independent of resistivity. This is, by definition, fast reconnection. Second, we usually expect the reconnection speed to be close to the turbulent eddy speed; the geometric ratios that enter the expression, i.e. the injection scale $l$ divided by the length of the reconnection layer $L$, are typically of order unity. Reconnection will occur on dynamical time scales. Finally, we note that in particular situations when the turbulence is extremely weak the reconnection speed can be much slower than the Alfvén speed. Strong magnetic field prior to reconnection presents such a case, which ensures that magnetic flux of opposite polarities can be accumulated prior to reconnection in solar flares (see LV99, Lazarian and Vishniac 2009).

More recently, Eq. (1) was derived using ideas based on the well-known concept of Richardson diffusion (Eyink et al. 2011). From the theoretical perspective this new derivation avoids rather complex considerations of the cascade of reconnection events that were presented in LV99. Eyink et al. (2011) also show that the LV99 model is closely connected with the idea of "spontaneous stochasticity" of magnetic fields in turbulent fluids.

The deep connection between magnetic turbulence and magnetic reconnection is thus evident. LV99 showed that the Goldreich and Sridhar (1995) model, which envisages mixing motions perpendicular to magnetic field lines, becomes self-consistent in the presence of magnetic reconnection given by Eq. (1). Eyink et al. (2011) showed that the established Lagrangian properties of 3D MHD turbulence require the LV99 reconnection with given by Eq. (1).

We note that a theoretical model of turbulent reconnection was suggested recently by Gao et al. (2012), based similarly to LV99 on the Goldreich and Sridhar (1995) theory of Alfvenic turbulence. Unlike LV99 theory, these authors apply a mean-field approach to the problem of magnetic reconnection and utilize the concept of hyper-resistivity, which has some difficulties (e.g. Eyink et al. 2011). It was further argued in Eyink et al. (2011) that any mean-field proof of fast reconnection is not tenable unless the reconnection rates obtained are strictly independent of the length-scales and time-scales of averaging.

### 3.2 Numerical Testing of LV99 Model

The first test of the LV99 model using three-dimensional (3D) simulations was performed in Kowal et al. (2009). LV99 is a model formulated in the MHD regime. Thus a set of MHD equations was solved in Kowal et al. (2009, 2012b). The boundary conditions and the manner of energy injection were varied between different simulations. In order to avoid the complications of strong compressibility, high-beta simulations were used.

For numerical simulations it is easier to control not $v_l$, but the energy injection power $P$. For sub-Alfenic injection the power in the turbulent cascade is $P \sim v_{turb}^2(V_A/l)$ or $v_l^4/(lV_A)$. The amount of energy injected during one Alfvén time unit $t_A$, which is constant in our models, is $t_A P \sim (L/V_A)v_l^4/(lV_A)$. Therefore $v_l^2 \sim (l/L)^{1/2}(Pt_A)^{1/2}V_A$. Substituting $v_l^2$ in Eq. (1) results in

$$V_{rec} \sim \left(\frac{l}{L}\right)(t_A P)^{1/2} \propto l\, P^{1/2}, \tag{2}$$

which is the prediction that was tested in the numerical studies. In what follows we refer to the injection power and scale using $P_{inj}$ and $l_{inj}$, respectively.

The setup of the reconnection simulations is illustrated in Fig. 3, which is a 2D cut, indicating the location of the diffusion region. The top and bottom of the computational domain contain equal and opposite field components in the $\hat{x}$ direction, as well as a sheared component $B_z$ (see the left panel of Fig. 3). Magnetic field lines enter through the top and bottom and are bent by the inflow $V_{in}$ as they move into the diffusion region. The diffusion region has a length $\Delta$ in the $\hat{x}$ direction and a thickness $\delta$ in the $\hat{y}$ direction (see the left panel of Fig. 3).

The numerical box is periodic in the $\hat{z}$ direction and the diffusion region extends through the entire domain. The projection of the magnetic topology on the $xz$ plane shows that the fieldlines in the upper region (solid lines in the right panel of Fig. 3) and in the lower region (dashed lines) are offset by an angle $\alpha$ determined by the strength of the sheared component $B_{0z}$. Once the incoming magnetic lines enter the diffusion region, they are reconnected

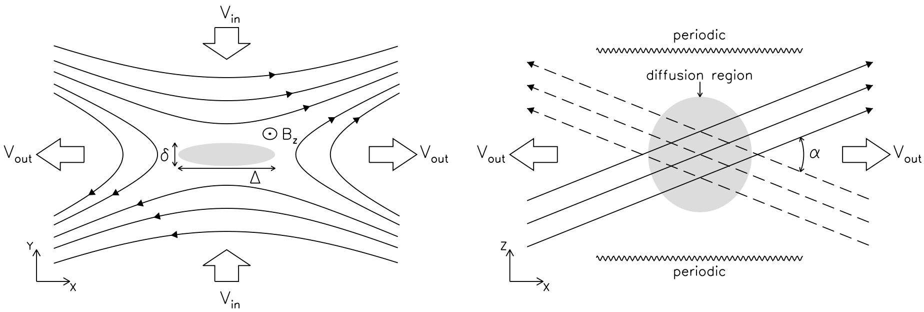


**Fig. 3** A schematic of magnetic field configuration projected on the $xy$ (*left*) and $xz$ (*right*) planes. *Left:* $xy$ projection of the magnetic field lines. The *gray area* describes the diffusion region where the incoming field lines reconnect. The longitudinal and transverse scales of the diffusion region are given by $\Delta$ and $\delta$, respectively. We use outflow and inflow boundary conditions in the $\hat{x}$ and $\hat{y}$ directions, respectively. *Right:* $xz$ projection of the magnetic field lines as seen from the top. *Solid* and *dashed lines* show the incoming field lines from the upper and lower parts of the domain, respectively. We see that the oppositely-directed field lines are not anti-parallel but are offset by an angle $\alpha$ determined by the strength of the sheared component $B_z$. The $\hat{z}$ boundary conditions can be open or periodic, depending on the model (from Kowal et al. 2009)

and the product of this process is ejected along the $x$ direction with a speed $V_{out}$ (the left panel of Fig. 3).

In Kowal et al. (2009), the turbulence was driven using a method described by Alvelius (1999), in which the driving term was implemented in the spectral space with discrete Fourier components concentrated around a wave vector $k_{inj}$ corresponding to the injection scale $l_{inj} = 1/k_{inj}$. In Kowal et al. (2012a), a new method of turbulence driving was employed. Individual eddies with random locations of their centers and random orientations, either to velocity or magnetic field, at random moments in time were introduced. This guarantees the randomness of the forcing with the new method. This new method drives turbulence directly in real space, in contrast with the previous approach; therefore, it can be applied locally. The turbulence is driven in a subvolume of the domain, whose size is determined by two scales: the radius $r_d$ on the $xz$ plane around the center of the domain and the height $h_d$ describing the thickness of the driving region from the midplane.

All models are evolved without turbulence for several dynamical times in order to allow the system to achieve stationary laminar reconnection. Then, at a given time $t_b$ we start driving turbulence by increasing its amplitude to the desired level, until $t_e$. In this way we let the system adjust to a new state. From time $t_e$, the turbulence is driven with the full power $P_{inj}$.

The reconnection rate was measured using the method introduced in Kowal et al. (2009) and described by the formula

$$V_{\mathrm{rec}} = \frac{1}{2|B_{x,\infty}|L_z}\left[\oint \mathrm{sign}(B_x)\boldsymbol{E}\cdot d\boldsymbol{l} - \partial_t \int |B_x| dA\right] \tag{3}$$

where $B_x$ is the strength of reconnecting magnetic component, $\boldsymbol{E}$ is the electric field, $dA$ is an area element of an $xz$ plane across which we perform the integration, $d\boldsymbol{l}$ is the line element separating two regions of the YZ plane defined by the sign of $B_x$, $|B_{x,\infty}|$ is the asymptotic absolute value of $B_x$, and $L_z$ is the width of the box. The measures obtained in this way were in good agreement with the measures obtained by calculating the inflow velocity of the plasma and magnetic field at the boundaries.

In Fig. 4, examples of $xy$-cuts (upper row) and $xz$-cuts (lower row) through the box are shown. The driving is applied in real space and a large number of individual eddies is injected in the magnetic field with random locations and random orientations.

Figure 5 shows averaged values of the reconnection speed $V_{rec}$ in models with turbulent power $P_{inj}$ varying by more than one order-of-magnitude, from 0.1 to 2.0, for both models with Fourier driving (black symbols) and with real-space driving (blue and red symbols). Filled symbols represent the averaged reconnection rate in the presence of turbulence. The dotted line corresponds to the reconnection rate without turbulence. The error bars show the time variance of $V_{rec}$.

The reconnection rates for models with different types of driving confirm the theoretical dependence of $V_{rec}$ on the injected power, which scales as $\sim P_{inj}^{1/2}$. There is no significant difference between models in which turbulence was driven in velocity and in magnetic field. This is in good agreement with the LV99 expectations that the reconnection rate should not depend on the nature of the turbulent driving.

These recent numerical studies confirmed the main predictions of LV99.[3] This motivated applications of the model to explain astrophysical phenomena from star formation to cosmic ray acceleration and gamma-ray bursts (Lazarian 2005, 2009; de Gouveia Dal Pino and Lazarian 2005; Zhang and Yan 2011; Santos-Lima et al. 2010; Lazarian and Yan 2012; Lazarian et al. 2012a). The most dramatic consequence of LV99 theory is that the magnetic flux is not frozen in turbulent fluids (Vishniac and Lazarian 1999). This prediction was strongly supported by the study in Eyink et al. (2011), where LV99 theory was related to the concept of the Richardson diffusion of magnetic field. The latter was recently demonstrated numerically in Eyink et al. (2013), providing an independent test of LV99. Future work should consider the dependence on the guide-field, which is important for the solar corona and other astrophysical applications.

### 3.3 2D and 3D Turbulent Reconnection

Studies of 2D reconnection were performed many years ago by Matthaeus and Lamkin (1985, 1986). The authors studied 2D magnetic reconnection in the presence of external turbulence, including the effects of multiple X-points as reconnection sites. An enhancement of the reconnection rate was reported, but this claim was not supported by the calculation of a long term average reconnection rate. Interestingly enough, a more recent study along the approach in Matthaeus and Lamkin (1985) was performed by Watson et al. (2007), where the effects of small-scale turbulence on 2D reconnection were carefully studied. However, no significant effects of the turbulence on reconnection were reported. A more optimistic conclusion is reached in Servidio et al. (2010) where reconnection on small scales with dimensionless inflow speed 0.1–0.3 was reported. However, this was happening on small scales, where the Sweet-Parker rates for the numerical set-up are comparable and therefore the implications for the large-scale reconnection were unclear. In fact, the theoretical model in Matthaeus and Lamkin (1985) does not predict the global reconnection rate.

We note that these studies did not include the effect of magnetic field wandering, which is at the core of the LV99. In view of the differences between 2D and 3D turbulence (see the corresponding discussion in Eyink et al. (2011)) it is not clear how to relate the 2D results with 3D reconnection. The aforementioned papers on 2D turbulent reconnection did

[3]After LV99 was published, Kim and Diamond (2001) produced a study arguing that turbulence will not change reconnection rates. The theoretical arguments in this study have been criticized by Lazarian et al. (2004) and Eyink et al. (2011).

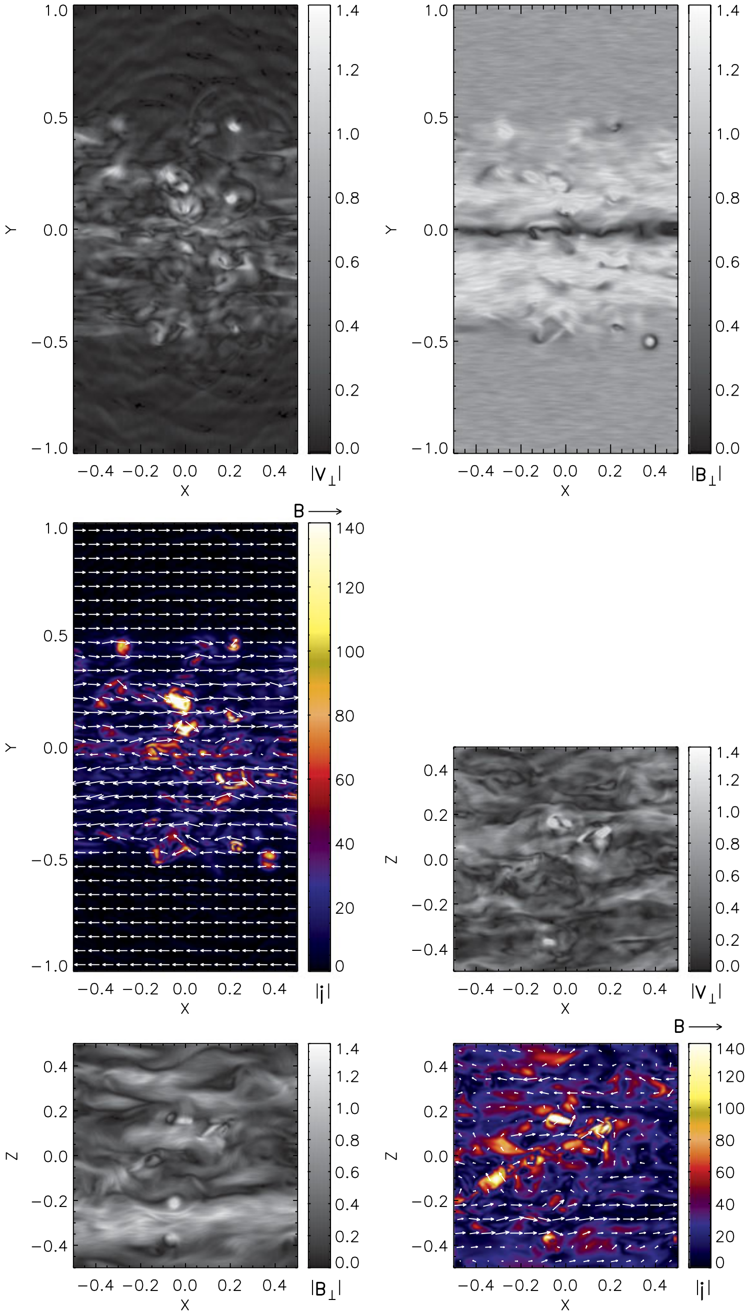


**Fig. 4** Topology and strength of the velocity field (*left panel*) and magnetic field (*middle panel*) in the presence of fully developed turbulence for an example model with the new driving method at time $t = 10$. In the *right panel* we show the distribution of the absolute value of current density $|\mathbf{J}|$ overlapped with the magnetic vectors. The images show the $xy$-cut (*upper row*) and $xz$-cut (*lower row*) of the domain at the midplane of the computational box. Turbulence is injected with power $P_{inj} = 1$ at scale $k_{inj} = 8$ directly in the magnetic field. From Kowal et al. (2012a)

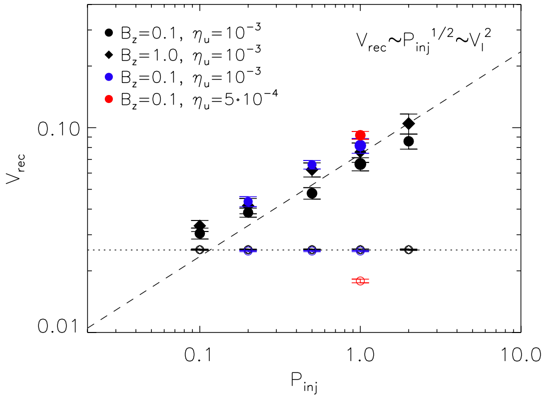


**Fig. 5** The dependence of the reconnection speed $V_{rec}$ on $P_{inj}$ including the new models, in dimensionless units as described in Kowal et al. (2012a). *Blue symbols* show models with the new driving, in which the eddies where injected in magnetic field instead of velocity, as in the previous models (*black symbols*). The *dotted line* corresponds to the Sweet-Parker reconnection rate for models with $\eta_u = 10^{-3}$. A unique red symbol shows the reconnection rates from a model with the new driving in velocity performed with higher resolution ($512 \times 1024 \times 512$) and resistivity coefficient reduced to $\eta_u = 5 \cdot 10^{-4}$. *Error bars* represent the time variance of $V_{rec}$. The size of symbols corresponds to the error of $V_{rec}$. From Kowal et al. (2012a)

not make predictions of how the reconnection should change with the level and properties of turbulence.[4]

Furthermore, the approach in Matthaeus and Lamkin (1985, 1986) is radically different from that in LV99. The former authors associate the increase of reconnection with the development of X-point, Petsheck type reconnection: thus in, e.g. Servidio et al. (2010), the modeling of 2D turbulent reconnection under the influence of Matthaeus and Lamkin (1985) approach was focused on detecting X-points. However, X-points are not a part of LV99 model. There, it is shown that the reconnection is fast even if the small-scale events happen at the low Sweet-Parker rate and correspond to Y-point reconnection. It is well known that MHD turbulence is very different in 2D and 3D, e.g. the Alfven modes that are identified in LV99 as the source of widening of the outflow region, are absent in 2D.

Whether 2D magnetic reconnection in the presence of turbulence is also fast is an interesting question, but due to the different physics the answer to this question does not provide much insight to understanding the real world 3D magnetic reconnection

### 3.4 LV99 Range of Applicability and Implications

The LV99 model of reconnection is applicable to collisional media, such as the ISM, which is both turbulent and magnetized, and where Hall-MHD reconnection does not work (Yamada 2007). For instance, for Hall-MHD reconnection to be applicable, it is required that the Sweet-Parker current sheet $\delta_{SP}$ width ibe smaller than the ion inertial length $d_i$. Thus, the "reconnection criterion for media to be collisionless" is $(L/d_i)^{1/2}/(\omega_c \tau_e) < 1$, which

[4]By itself, the measurements of current densities in the aforementioned papers do not constrain the reconnection speed much. Indeed, one can get transient enhancements of current densities within slow Sweet-Parker reconnection by decreasing $\Delta$. One cannot reconnect much flux this way, however, as the decrease of $\Delta$ would choke off the outflow and related magnetic reconnection.

presents a stringent constraint on the possible rate of collisions. As a result magnetic reconnection is mediated by the Hall-MHD only if the extent of the current sheet $L$ does not exceed $10^{12}$ cm. These are scales too small compared to the scales at which magnetic fields in the ISM interact.

At the same time, the LV99 model works for collisionless media and it shows that the microphysics of collisionless reconnection events does not change the resulting reconnection rates. This point was further analyzed in Eyink et al. (2011) who concluded that for most of astrophysical collisionless plasmas, the LV99 model should be applicable, provided that the plasma is turbulent. The most stringent criterion for the application of LV99 theory coincides with the applicability of the MHD approximation—see Sect. 4 below.

Solar flares inspired much of the earlier research on reconnection (Pneuman 1981; Priest and Forbes 2002). Stochastic reconnection provides an explanation for solar flares that does not involve plasma microphysics. Indeed, an important prediction of the LV99 model is related to the *reconnection instability* that arises in the situation when the initial structure of the flux prior to reconnection is laminar. This allows magnetic flux to accumulate. Eventually, tearing and other instabilities enhance the reconnection rate and provide 3D turbulence. This turbulence excites faster reconnection, creating positive feedback which results in a flare (Lazarian and Vishniac 2009). This "reconnection instability" can explain the bursty character of reconnection in solar flares and also gamma ray bursts (Lazarian et al. 2003; Zhang and Yan 2011). Furthermore, the reconnection instability can be triggered by turbulence from adjacent reconnection sites, as observed in Sych et al. (2009).

We should mention that observations of solar flares are consistent with LV99 predictions. For instance, observations of the thick reconnection current outflow regions observed in solar flares (Ciaravella and Raymond 2008) were predicted within LV99 model—at a time when the competing plasma Hall models were predicting X-point localized reconnection. However, as plasma models have evolved to include tearing and formation of magnetic islands (Drake et al. 2010)—see Sect. 5—one has to be more quantitative in comparing observations with the predictions from the competing theories. The corresponding comparison was done in Eyink et al. (2013). There it was shown that the differences between the LV99 predictions and the measured thickness of the reconnection layers in Ciaravella and Raymond (2008) arises from the isotropic manner of turbulence driving assumed for the sake of simplicity in LV99 theory. If a more relevant anisotropic driving arising from magnetic reconnection is accounted for, a good quantitative agreement between the measured thickness of the reconnection regions and LV99 predictions can be obtained.

In the process of testing LV99 theory, one should keep in mind that, unlike Sweet-Parker reconnection, the turbulent scenario exhibits outflow layers which consists of a multitude of fractal current sheets. The thickness of an individual current sheet may be very narrow and these may be dominated by anomalous plasma effects. Thus additional care should be applied while testing the theory with in situ measurements.

The concept of flux-freezing violation induces numerous consequences for different fields of astrophysics. For instance, star formation theory was formulated in the assumption of magnetic flux being well frozen into plasmas with flux-to-mass ratio being changed due to the diffusion of neutrals. Magnetic flux diffusion induced by turbulent reconnection leads to the removal of magnetic flux from the star formation regions. This possibility was discussed in Lazarian (2005) and was numerically confirmed in Santos-Lima et al. (2010). Further theoretical studies of a new way of removing of magnetic flux from clouds and cores are presented in Lazarian et al. (2012a).

We note that the turbulence that we consider may be either pre-existing or generated within the reconnection layer itself. In most astrophysical situations the former situation is more common. Therefore, the issue that one has to answer dealing with reconnection in astrophysical systems is how the pre-existing turbulence is accounted for in the reconnection processes. Apparently, the laminar approximation is not a good assumption for most of astrophysical high-Reynolds-number fluids.

## 4 Synergy of MHD and Plasma-Based Approaches to Reconnection

While our review is focused on fast magnetic reconnection that takes place in MHD regime, in this section we sketch the relation with some different directions of reconnection research. First of all, if the original models of magnetic reconnection, i.e. Sweet-Parker and Petschek reconnection, are distinctly regular and laminar, the models that now are considered most promising, whether turbulent, as we discuss in this review, or plasmoid-type (Karimabadi et al. 2013), include the distinct effects of stochasticity. This is a remarkable shift of paradigm. Indeed, when LV99 model was introduced, its main competitor was X-point Hall reconnection.

As we mentioned earlier, the LV99 theory based on MHD is not applicable to plasmas unless the expected turbulent broadening of the outflow region is *substantially* larger than the ion Larmor radius. Indeed, below the latter scale, no MHD description of the turbulent magnetic field wandering is applicable. Only when the reconnection region is $\sim \alpha\rho_i$ then one can talk about MHD turbulence broadening of the outflow region. The exact value of $\alpha$ is difficult to define theoretically. A possible guess is that it should be sufficiently large, e.g. in the range of $10^2$ or $10^3$ for the magnetic wandering not to be strongly affected by plasma effects. For thinner current sheets we are in the regime where we expect to be the domain of plasmoid reconnection. This is definitely the regime of magnetic reconnection in magnetosphere (see the discussion in Eyink et al. (2011)) and possibly over parts of the solar wind. The two examples present important cases of space plasmas that are intensively studied through in situ observations.

The criterion of the turbulent broadening depends on the level of turbulence; in the case when the initial magnetic configuration is laminar or only slightly turbulent, plasma instabilities, e.g. tearing mode, are expected to dominate the initial dynamics of magnetic reconnection. However, both PIC simulations (e.g. Daughton et al. 2011; Karimabadi et al. 2013) and MHD simulations (e.g. Hood et al. 2009; Beresnyak 2013) (see also Sect. 6 below) testify that turbulence is generated in the process of reconnection. This turbulence should modify the reconnection. One possible effect of turbulence is the suppression of instabilities, e.g. the tearing instability, and the transition to pure turbulent reconnection (see also Rapazzo et al. 2013) . If this is true, then plasma effects can trigger turbulent magnetic reconnection. However, the identification of true turbulence in 3D MHD simulations is difficult, due to the limited range of spatial scales. Further work is needed to identify whether, for example, the fine-scale structures and complex flows identified by Hood et al. (2009) correspond to a turbulent cascade of energy to small-scales.

## 5 Some Other Approaches to Turbulent Reconnection in MHD

We now consider some different aspects of the interaction between turbulence and reconnection within the MHD framework. An important approach towards understanding the destabilisation of an initially laminar reconnection region can be traced back to the work of Shibata and Tanuma (2001). This paper proposes a *fractal reconnection* scenario, in which an initial current sheet thins and becomes subject to tearing instability (if the sheet length is longer than the critical wavelength for onset of tearing); the same process repeats on increasingly smaller scales, leading to a fractal distribution of magnetic islands on scales down to a microphysical limit such as the ion Larmor radius. At the same time, islands or plasmoids ejected during the reconnection process may coalesce with others to form larger plasmoids. Such a process is indeed observed in MHD simulations (Tanuma et al. 2001). The instabilities, like tearing instability, open up the reconnection layer enabling a wide outflow.

Recently, Barta et al. (2010, 2011) used a 2.5D numerical MHD simulation with Adaptive Mesh Refinement to demonstrate the formation of plasmoids on a very wide range of scales. Further recent studies of fragmentation and coalescence of plasmoids include Loureiro et al. (2009, 2012), Bhattacharjee et al. (2009). These instabilities can lead to fast reconnection (Uzdensky et al. 2010). Similar merging and coalescence of plasmoids is also widely observed in PIC simulations (e.g. Drake et al. 2010; Karlicky et al. 2012; Markidis et al. 2012; Huang and Bhattarcharjee 2013).

Another idea which suggests a complex pattern of reconnections is "recursive reconnection" (Parnell et al. 2008). This numerical model, comprising two opposite-polarity sources interacting with an overlying field, illustrates the role of magnetic topology described further in Sect. 6. Reconnection can cause both opening and closing of magnetic flux, as closed field interacts with open field: notably, this can happen recursively, with field lines opening and closing repeatedly. This both enhances the global reconnection rate and leads to more distributed heating.

Finally, we mention the interaction between MHD models of reconnection and kinetic-scale turbulence—see also Karimabadi et al. (2013). In many astrophysical plasmas, there is a complex interplay between large-scale fluid phenomena and microscales which are kinetic. Indeed reconnection on MHD scales may itself generate kinetic instabilities (see Brown et al. 2013, this issue), whilst kinetic turbulence may influence the global reconnection dynamics.

Numerical simulations of collisionless plasma, such as Shay et al. (1998, 2004) and much subsequent work, have been encouraging in showing that collisionless dissipation on small scales may play an important role in achieving fast reconnection; for example, in the solar corona. Furthermore, "anomalous resistivity", driven by kinetic turbulence within current sheets, in many cases almost certainly plays a far more important role in reconnection which is described by MHD on the global scale, than classical Spitzer resistivity. Most MHD simulations of reconnection actually rely on some kind of anomalous resistivity, although the resistivity model is not usually physically-motivated: see Gordovskyy et al. (2013b) for a recent attempt to include a more realistic resistivity model, based on ion-acoustic turbulence, in a MHD simulation. Predictions of anomalous resistivity from current-driven instabilities leading to microturbulence, such as by Petkaki et al. (2006) and Buechner and Elkina (2006), have important consequences for MHD reconnection. However, a full understanding of the coupling between global fluid models and kinetic physics remains a subject for future investigation.

## 6 Complex and 3D Fields and the Formation of Fine Structure

Using the solar corona as an example, we will now show that a state of topological complexity with many localised current sheets—a state of turbulent reconnection—is natural in astrophysical plasmas. A wealth of observations from a series of space-borne telescopes—such as Solar Dynamic Observatory, and, most recently, Hi-C (Cirtain et al. 2013)—indicate that the corona is highly dynamic and is full of fine structure (on scales at least down to present resolution limits).

### 6.1 Current Sheet Formation in the Solar Corona

The strong solar coronal magnetic field (with low $\beta = 2\mu_0 p/B^2$) is rooted in the dense photosphere, where turbulent velocities move the footpoints of the magnetic field. The existence of current sheets in the solar coronal fields has been predicted to arise in the following ways: (i) Complex footpoint motions in a simple initial field geometry, or “field line braiding”. (ii) Complex initial fields with simple motions—including footpoint displacements in fields with X-points, separators, separatrices etc., emergence of new magnetic flux and the effects of discrete photospheric flux tubes. (iii) Simple initial fields with simple motions e.g. forced magnetic reconnection and kink instability due to twisting motions. We now discuss each of these three ideas.

The idea of current sheet formation due to *braiding* of the coronal flux tubes originates with Parker (1972). It was proposed that as the footpoints of coronal flux tubes are slowly moved by complex photospheric motions, the flux tubes develop a braided pattern for which no smooth force-free equilibrium can be found. In consequence, the field, in the ideal MHD limit, develops discontinuities (infinitely-thin current sheets). The coronal field thus is in a state of turbulent reconnection, heating the coronal plasma through a process dubbed “topological dissipation”. Parker proposed a simple theoretical paradigm for this process, consisting of an initially uniform, straight field embedded in a perfectly-conducting plasma, between two conducting planes (representing the photosphere), subject to slow motions of the photospheric footpoints which lack symmetry. The subsequent equilibrium states of the field are constrained by the footpoint connectivity.

The “Parker” model has led to a much subsequent work over 40 years; such as, recently Low (2006), Rapazzo et al. (2007, 2013), Berger and Asgari-Targhi (2009). It is broadly established that fine structure, including localised, very strong currents, indeed arises. However, there is still no consensus on the inevitability of true discontinuities (infinite currents) in the ideal MHD limit, although Van Ballegoijen (1985) provided a methodology to find a force-free equilibrium for any continuous footpoint motions, suggesting there are no discontinuities. For example, Ng et al. (2012) use Reduced-MHD (RMHD) simulations with random footpoint motions to show that the energy dissipation rate is independent of the resistivity, and that reconnection is much faster than Sweet-Parker. Wilmot-Smith et al. (2010) and Pontin et al. (2011) create a field representing a simple braid of three flux tubes, which is close to force-free equilibrium, using a Lagrangian relaxation scheme. They then use a 3D MHD simulation to show that this develops many small-scale current sheets and subsequently dissipates free magnetic energy by reconnection. It should be noted, however, that these simulations consider loops with very weak transverse magnetic field components and hence with very little free magnetic energy (i.e. the fields are always very close to a current-free state); hence, their relevance to heating coronal Active Regions is questionable. The same difficulty applies to the many works which use the RMHD approach, in which a weak transverse field component is assumed.

Recent high resolution solar observations from Hi-C (Cirtain et al. 2013) indicate the presence of untwisting coronal loops, which are suggested to be consistent with dissipation of braided fields. However, as noted by Cargill (2013), these observations are equally consistent with kink-unstable twisted loops (see Sect. 7 below). Indeed, both braiding and twisted loop models results in a network of localised thin current layers, with turbulent reconnection.

It is very easy to form current sheets by footpoint motions of fields with complex topology (i.e. with regions of different fieldline connectivity). For example, shearing the footpoints of a 2D field configuration with a separatrix and multiple flux domains naturally forms a current sheet along the separatrix (e.g. Vekstein et al. 1992), since neighbouring field lines on different sides of the separatrix may have very different footpoint displacements, leading to a discontinuity in the field. Similarly, the fact that the photospheric footpoints of the coronal field are actually concentrated into discrete isolated flux tubes naturally leads to the formation of discontinuities (in the ideal limit) within the coronal magnetic field. Thus, motions within flux sources, or motions of the flux sources themselves, inevitably generates coronal reconnection (Browning et al. 1986; Lothian and Browning 1995). This scenario has been dubbed "flux tube tectonics", and explored in some depth (Priest et al. 2002). Furthermore, models of new flux emerging into the corona from the solar interior involve the interaction of two flux systems, again resulting in current sheet formation and considerable topological structure, as demonstrated in 3D numerical simulations (e.g. Archontis et al. 2005; Parnell et al. 2010).

In fact, even the simplest field topologies and footpoint velocity profiles can generate fine-scale structure in the corona. One example has already been mentioned in Sect. 2—namely, forced reconnection. Here, a simple sinusoidal disturbance of a sheared force-free field in a slab can generate a current sheet, leading to reconnection and a chain of magnetic islands (Hahm and Kulsrud 1985; Vekstein and Jain 1998; Jain et al. 2005). If the external disturbance consists of multiple modes in different directions, then a series of current sheets will be formed at the various resonant surfaces, leading to overlapping islands with stochastic field lines (Onofri et al. 2004). Another example is the nonlinear kink instability (see Sect. 7): even smooth rotational motions of the footpoints of simple cylindrical flux tubes can lead to the formation of a fragmented current structure with turbulent reconnection.

An important consequence of the ubiquitous presence of small-scale structure in the solar atmosphere is that the resulting state of multiple reconnections may heat the coronal plasma. Whilst it is generally accepted that large solar flares are a result of release of stored magnetic energy by reconnection in a large-scale current sheet, a promising scenario for maintaining the overall high temperature of the corona is the combined effect of many very small flare-like events known as "nanoflares" (Parker 1988). We return to the coronal heating problem in Sect. 7.

In summary, in the solar corona the topology is complex, and hence multiple reconnection sites are likely to exist (Maclean et al. 2009), with reconnection usually being 3D. The coronal field is predicted to be in a constant state of turbulent reconnection. This theoretical picture is supported by observations. For example, observations of Type III radio bursts, which are produced by beams of non-thermal electrons in the corona, indicate that energy release is highly fragmented both in space and time (Chen et al. 2013). A similar picture is likely to pertain in other astrophysical plasmas.

### 6.2 3D Reconnection Models

Whilst classical reconnection models are two-dimensional, as outlined in Sect. 2, most astrophysical phenomena are not well-described by 2D models, and much recent research shows that the reconnection in 3D differs in quite fundamental ways. Even the definition of reconnection is less clear. Schindler et al. (1988) suggest that reconnection can be identified through the existence of localised parallel electric fields. Reconnection in 3D can occur at 3D magnetic nulls—but does not require the presence of nulls; in contrast to 2D reconnection which requires an X-point (a 2D null) or a field reversal (although 2.5D reconnection, i.e. including a guide-field, also does not require nulls). Furthermore, the topological properties of 3D reconnection can be quite different. Whereas in 2D reconnection, there is a simple pair-wise reconnection of flux tubes, with two incoming flux tubes "breaking and re-joining" to form two flux tubes in the outflow, the situation is more complex in 3D (Priest et al. 2003; Cargill et al. 2010). In general, due to counter-rotating flows within the diffusion region, it is not possible to uniquely match pairs of inflow and outflow fieldlines (Priest et al. 2003; Pontin et al. 2005). The properties of 3D reconnection are reviewed by Pontin (2011).

The topology of the magnetic field may be summarised through knowledge of the "magnetic skeleton" (Bungey et al. 1996). This comprises: *field sources* on the photospheric boundary (which are usually, more or less, discrete); *magnetic null points* (usually 3D); a set of flux domains bounded by *separator surfaces* (the 3D analogue of 2D separatrices); and *separator lines*, which are the intersection of separators. Such topological features form the likely sites of magnetic reconnection, as well as *Quasi Separatrix Surfaces* (Titov et al. 2002; Demoulin 2006) which are layers of strong divergence in field line connectivity. Reconnection may occur at 3D null points (Priest and Titov 1996; Craig and Fabling 1996) but also in the absence of nulls, with separator lines playing an important role (Longcope and Cowley 1996; Parnell et al. 2010).

Understanding the nature of reconnection in 3D—and the inevitable interactions with turbulence—is an important subject of future research.

## 7 Relaxation in Turbulent Reconnecting Plasmas

An important consequence of turbulent reconnection in astrophysical plasmas is the dissipation of stored magnetic energy. A large-scale energy release may cause a solar flare, whereas the combination of many smaller energy releases may be the source of heating required to maintain coronal plasma at temperatures of over a million degrees Kelvin. In order to predict the energy release, it is not necessary to calculate the detailed dynamics, if it is assumed that the field relaxes towards the state of lowest possible magnetic energy. The appropriate constraint for such relaxation, in the presence of multiple localised reconnections, is that the global magnetic helicity

$$K = \int_V \mathbf{A} \cdot \mathbf{B} \, dV, \tag{4}$$

is conserved, where $\mathbf{A}$ is the vector potential (Taylor 1974, 1986). This follows since reconnection transfers helicity between flux tubes, without creating or destroying helicity. Also, it can be shown that, if dissipation is confined to narrow current layers, with width much less than the global length scale, then fractional helicity dissipation is much less than energy dissipation (Berger 1984; Browning 1988). Note that in a volume in which magnetic fieldlines cross the bounding surface (such as the corona, in which field lines cross the photosphere), then the relative helicity must be used (Berger and Field 1984; Finn and Antonsen 1985). The minimum energy state with conserved helicity is a constant-$\alpha$ or linear force-free field:

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}, \tag{5}$$

where $\alpha$, which is the ratio of parallel current to magnetic field, is spatially constant. Relaxation theory was developed by Taylor (1974) to explain the reversal of toroidal field in Reverse Field Pinch devices, and has been successfully applied also to other laboratory devices such as spheromaks (Taylor 1986; Jarboe 1994).

Heyvaerts and Priest (1984) first applied this idea to the solar corona, proposing that the coronal field is continually stressed by slow photospheric footpoint motions, causing it evolve through a series of nonlinear force-free fields satisfying (5) but with spatially-varying $\alpha$. The field then relaxes to a minimum energy state, conserving helicity whilst releasing free magnetic energy as heat. This idea was developed by many others (e.g. Browning and Priest 1986; Browning et al. 1986; Dixon et al. 1988; Vekstein et al. 1993; Wolfson

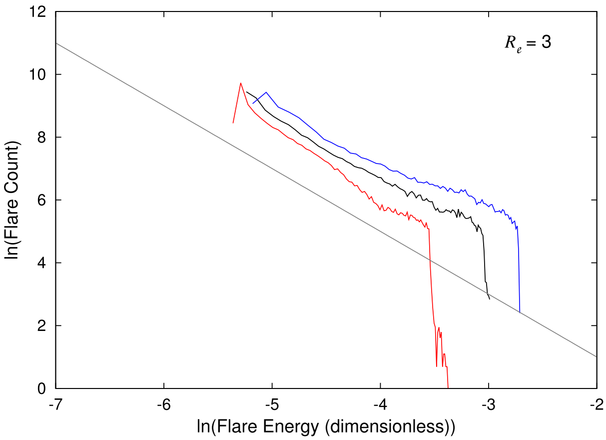


**Fig. 6** The distribution of event frequencies against the magnitude of the energy release for cylindrical twisted loops with different aspect ratios ($L/R$, where $L$ and $R$ are, respectively, the loop length of radius). This shows a power law distribution as expected for nanoflares. From Bareford et al. (2011)

et al. 1994; Kusano et al. 1994; Lothian and Browning 2000), and generalised to different boundary conditions (Browning 1988; Dixon et al. 1989)—but it remained unclear how far free magnetic energy could build up before the field relaxed. Thus, the energy release depended on an unknown "relaxation time". This problem was resolved by Browning and Van der Linden (2003), who suggested that relaxation could be triggered by the onset of ideal instability, such as kink instability in a twisted loop. In the case of a twisted cylindrical loop in which the current profile arising from photospheric motions was parameterised by a family with piecewise-constant $\alpha$, the energy release was shown to depend on the current profile at the point of instability onset (Browning and Van der Linden 2003).

Subsequently, Bareford et al. (2010, 2011) developed a relaxation-based model of coronal heating due to random photospheric footpoint driving. The field in a cylindrical loop evolves randomly through a series of equilibria until the threshold for ideal kink instability is reached: at this point, the energy dissipated during a helicity-conserving relaxation to a constant-$\alpha$ field is calculated. The process is repeated, with a cycle of stressing the field followed by relaxation: thus, a distribution of heating events or "nanoflares" is built up. In the case of localised twisting motions, in which the loop thus carries zero-net current, a power-law distribution of event size vs. occurrence frequency can be generated (Bareford et al. 2011); see Fig. 6. The average rate of energy dissipation, due to the repeated driving and relaxation, is sufficient for heating a coronal Active Region. This provides an *a priori* prediction of the distribution of nanoflare energies, whose combined effect heats the corona, as first postulated by Parker (1988).

A strength of these models is that they require significant free energy to be stored before the onset of kink instability and heating, thus providing sufficient heating for Active Regions requirements; see the discussion in Bareford et al. (2010), showing agreement with the requirements on transverse field set by Parker (1988). This contrasts with RMHD models and similar models which use a small transverse field component. It is interesting to investigate the behaviour of repeated heating events (e.g. Jain et al. 2005). Preliminary 3D MHD simulations (Gordovskyy, private communication) suggest that a repeated series of heating events may indeed be produced if the footpoint driving is maintained. On the other hand, Rapazzo et al. (2013) suggest that, if the driving motions are turbulent, the fields may become sufficiently incoherent that kink instability cannot arise.

Observational evidence to support Taylor's hypothesis—of helicity-conserving relaxation to a minimum energy state—is found in a wide range of laboratory experiments (e.g.

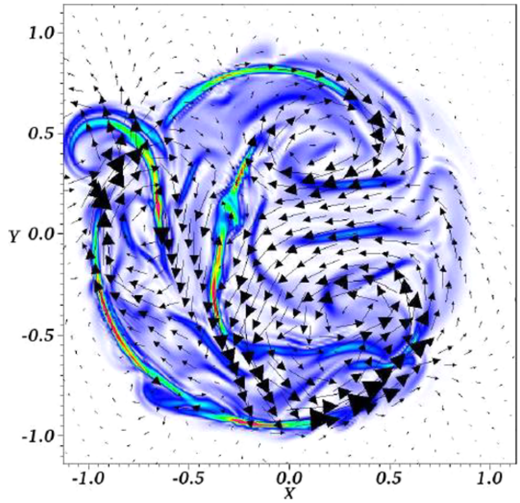


**Fig. 7** The distribution of currents (colour scale) and velocities (*arrows*) at the loop midplane during the later stages of relaxation in a kink-unstable twisted loop. From Hood et al. (2009)

see Taylor (1986) and references therein). Furthermore, relaxation towards a constant-$\alpha$ state is observed in solar flares (Nandy et al. 2003). Further verification of Taylor relaxation in coronal loops, as well as understanding of *how* the relaxation takes place, is provided by 3D MHD simulations of twisted cylindrical coronal loops (Browning et al. 2008; Hood et al. 2009; Bareford et al. 2013). These simulations consider an initially force-free cylindrical twisted loop which is linearly unstable to the ideal kink mode. In the nonlinear phase of the kink instability, a helical current ribbon forms, leading to fast reconnection and dissipation of magnetic energy, with the field subsequently reaching a new equilibrium with lower energy.

Browning et al. (2008) show that helicity dissipation is much less than energy dissipation, and that the final relaxed state is close to a constant-$\alpha$ field, consistent with Taylor relaxation. The relaxation mainly occurs as the initial helical current sheet breaks up and fragments (Hood et al. 2009), leading to distributed reconnection throughout the loop volume, with a turbulent velocity profile, in which outflows from one current sheet drive reconnection in its neighbour (see Fig. 7). The initially monolithic current sheet stretches and bifurcates, with the smaller sheets then subsequently splitting repeatedly, in a manner somewhat analogous to the 2D "fractal reconnection" models described in Sect. 5. The $\alpha$ profile becomes more uniform due to the multiple reconnections, as suggested long ago in the Tangled Discharge Model (Rusbridge 1977, 1991); again, we see an association between reconnection and fieldline wandering (see Sect. 3). The loop is heated throughout its volume.

The Taylor hypothesis only predicts the state of lowest possible energy, which may not actually be attained if there are other constraints on the dynamics (Bhattacharjee et al. 1980), or simply if there is not enough free energy to drive the relaxation. In the case of a loop twisted by localised photospheric motions, which has zero net-current, the extent of the disruption within the nonlinear phase of the instability is confined to a region with about 1.5 times the original loop radius; this leads to a partial relaxation in which the magnetic field outside this is undisturbed (Hood et al. 2009; Bareford et al. 2013).

Yeates et al. (2010), based on simulations of an initially braided coronal loop, propose that additional topological constraints, associated with the mapping of field lines from one end of the loop to the other, may prevent full Taylor relaxation. However, their simulations consider initial fields with little much free energy, and their final state in energetic terms is actually very close to the constant-$\alpha$ state—which is a potential field in this case. So Taylor theory still provides a good estimate of the energy release, despite the incomplete relaxation.

Nevertheless, it is clear that full relaxation can never really occur in an astrophysical plasma which is necessarily unbounded—unlike finite-volume laboratory plasmas. So relaxation must necessarily be limited spatially by the extent of the region of turbulent reconnection: a new theory of partial relaxation for unstable cylindrical loops which accounts for this has been recently proposed by Bareford et al. (2013). Furthermore, relaxation is similarly restricted by the onset of such a turbulent reconnecting state: it is quite possible for a field to remain in a state with free energy—which is not the minimum energy state—until relaxation is somehow triggered. As discussed above, an example of such a trigger is the onset of ideal MHD instability, but there are likely to be many other possible mechanisms.

A full understanding of relaxation in astrophysical plasmas requires much further research.

## 8 Turbulent Reconnection and Particle Energisation

The origin of high-energy particles in solar flares is a long-standing problem in astrophysics, as well the acceleration of cosmic rays. Proposed mechanisms include both turbulence or acceleration by direct electric fields in a reconnecting current sheet (see reviews Miller et al. (1997), Zharkova et al. (2011)). However, turbulence models tend to rely on an arbitrary turbulent field which is not related to the reconnection which is the primary source of energy-release in a flare, whilst reconnection models with a localised coronal current sheet suffer with difficulties, such as bringing in a large number of particles into a small current sheet volume. Many aspects of flare particle acceleration can be explained by combining turbulence with reconnection. This topic has been extensively reviewed elsewhere (e.g. Vlahos et al. 2009; Cargill et al. 2012), as well as some aspects being discussed by Lazarian et al. (2012b); we mention here some aspects of this topic which relate directly to our earlier discussions of turbulent reconnection.

Firstly, the turbulent reconnection LV99 paradigm, described in Sect. 3, provides effective particle acceleration through First-order Fermi acceleration—in which particles bounce between converging magnetic mirrors. Figure 8 illustrates the First-order Fermi acceleration that takes place within a turbulent reconnection region (de Gouveia Dal Pino and Lazarian 2005; Lazarian 2006).[5] The acceleration happens as particles bounce back and forth within shrinking magnetic loops (see Fig. 8). Recently, the acceleration of cosmic rays in reconnection has been invoked to explain results on the anomalous cosmic rays obtained by Voyager spacecrafts (Lazarian and Opher 2009; Drake et al. 2010), the local anisotropy of cosmic rays (Lazarian et al. 2012b) and the acceleration of cosmic rays in clusters of galaxies (Brunetti and Lazarian 2011). Naturally, this process of acceleration widespread and not limited to these examples. Numerical studies of the particle acceleration have shown differences in the acceleration process between 2D and 3D and confirmed the first-order Fermi nature of the acceleration in turbulent reconnection layers (Kowal et al. 2011, 2012b).

The breakup of long current sheets into a chain of magnetic islands (Sect. 5) also has consequences for particle acceleration (Kliem 1994; Li and Lin 2012). Gordovskyy et al.

[5]The predicted spectrum without taking the backreaction of the accelerated particles is $N(E)dE \sim E^{-5/2}dE$. Considerations in Drake et al. (2006) suggest that the spectrum of the particles can get shallower if the backreaction is taken into account.

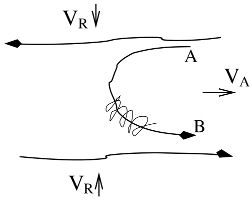


**Fig. 8** First order-Fermi acceleration as cosmic rays bounce within a 3D loop of reconnected flux that shrinks due to magnetic reconnection. From Lazarian (2005)

(2010a, 2010b) showed that two populations of accelerated particles arise in this case: a particle population trapped in the growing magnetic islands gains substantial energy, whereas particles remaining on open fieldlines are predominantly thermal.

Particles can be accelerated in fields with turbulent current sheets, such as those arising from braiding footpoint motions (Turkmani et al. 2006) (see Sect. 6.1). Also, the fragmented current sheets in unstable twisted loops (see Sect. 7) provide an effective means for distributed acceleration of charged particles in flares, with acceleration produced by the parallel electric fields within the current sheets. Using a relativistic guiding-centre test particle code coupled to 3D MHD situations, Gordovskyy and Browning (2011) and Gordovskyy and Browning (2012) show that particles gain energy through a series of almost discontinuous jumps, as they randomly encounter current sheets, in a manner reminiscent of earlier cellular automaton models (Vlahos et al. 2004)—see Fig. 9.

As the loop first becomes kink-unstable, particles are accelerated in the helical current ribbon which is quite radially localised, and leads to a narrow distribution of energetic particles. However, as described in Sect. 7, the current sheet breaks up into a distributed structure. Thus, particles are accelerated throughout the loop, and the loop quickly fills with energetic particles. The loop expands somewhat as it reconnects with the surrounding field, and hence the spatial extent of the energetic particles grows in time. The particle energy spectrum develops a non-thermal tail.

The particle spectrum is somewhat sensitive to the assumed resistivity profile. Assuming a rather high value of a uniform background resistivity (Turkmani et al. 2006) tends to over-estimate the number of accelerated particles (Gordovskyy and Browning 2012). If a localised current-dependent resistivity is used, the fraction of energetic particles can be relatively small, typically 5–10 %, validating the use of test particle modelling in this case. The increased numerical resolution of the more recent simulations may also explain the decrease in the fraction of energetic particles compared with earlier work, since the current sheets are better resolved; see further discussion in Cargill et al. (2012).

In cylindrical loop models, energetic particles are inevitably quickly lost through the ends of the loop. This may be mitigated by the effects of fieldlines convergence at the footpoints (Gordovskyy et al. 2013a); but in fact, few energetic particles are mirrored as they tend to have very small pitch-angles, a consequence of direct electric field acceleration. The confinement of particles within the loop is substantially modified by the occurrence of collisions within the dense chromosphere at the loop footpoints: this causes pitch- angle scattering, allowing more particles to be reflected and confined with the loop (Gordovskyy et al. 2013a). The time-evolving energy spectrum in a loop with field line convergence, and incorporating the effects of collisions with the stratified background plasma, is shown in Fig. 10.

Recently, a more self-consistent model of particle acceleration and transport in a twisted coronal loop has been developed: this considers a curved loop, twisted by localised footpoint motions, within a gravitationally-stratified atmosphere. The effects of transport and acceleration are incorporated, including collisions as well as acceleration by direct electric fields in a fragmented current sheet, with an anomalous resistivity dependent on the particle

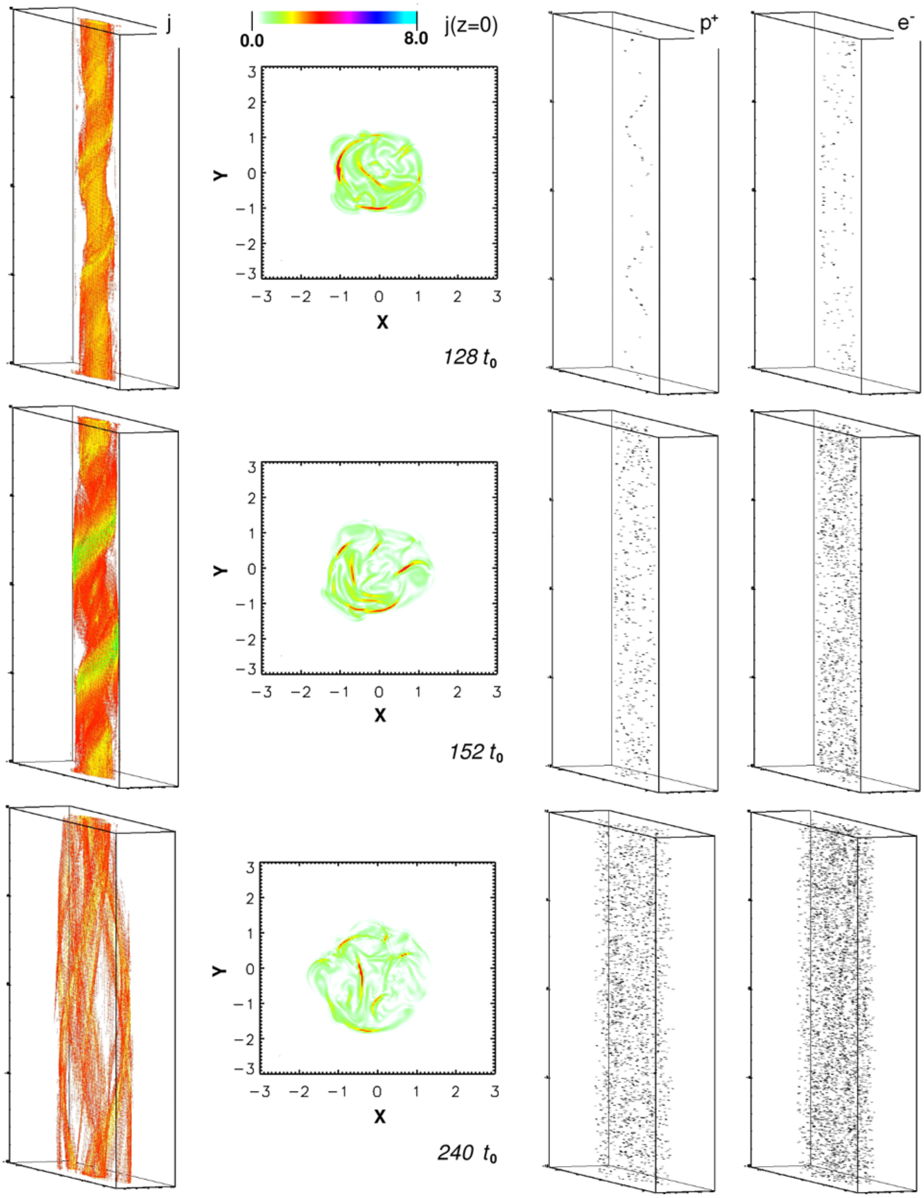


**Fig. 9** Particle acceleration in a kink-unstable twisted loop due to fragmented current sheets. Showing (from *left* to *right*), current isosurfaces, current at the midplane and spatial distributions of protons and electrons, at successive times. From Gordovskyy and Browning (2012)

drift velocity (Gordovskyy et al. 2013b). Particles are mainly accelerated both at the loop top and near the footpoints. Synthesised Hard X-ray emission is calculated, with footpoint and looptop sources which evolve through the flare event.

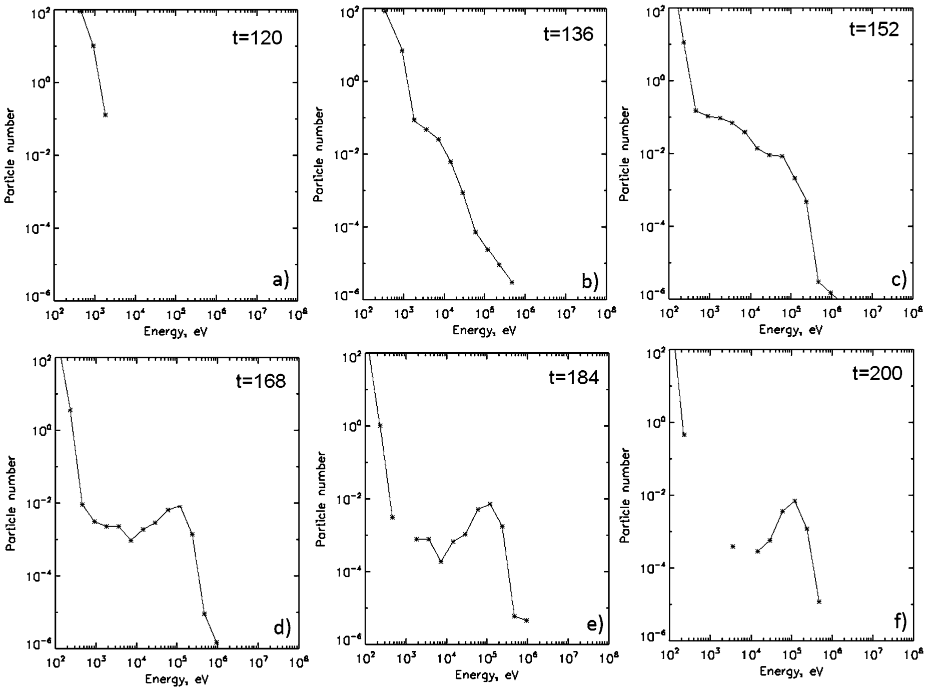


**Fig. 10** Electron energy spectra in a kink-unstable twisted loop with field line convergence towards the chromosphere, including the effects of collisions with the dense chromospheric plasma on the test particles, at a series of times through the flare. From Gordovskyy et al. (2013a)

## 9 Summary

Turbulence is a common—almost universal—state for astrophysical plasmas. Magnetic reconnection, which is an important process for restructuring of magnetic fields and dissipation of stored energy, interacts with turbulence in many ways. In this paper, we have given an indication of some ways in which our understanding of reconnection, within the magnetohydrodynamic framework, is affected by taking account of the presence of turbulence. In particular, we have shown how turbulence may resolve the long-standing fast reconnection problem, and that a complex state of turbulent reconnection naturally arises in astrophysical plasmas.

Our review is complementary to the reviews in this volume that investigate the possibility of achieving fast magnetic reconnection appealing to plasma effects, e.g. plasmoid reconnection. The relation between these two approaches requires further studies; in particular, at sufficiently small scales, the MHD description of the turbulent field wandering is not applicable and thus the model of turbulent reconnection we described is not applicable either. At the same time, turbulence arising from the reconnection process that is reported in both PIC and MHD simulations initiated with laminar magnetic fields is indicative that turbulent reconnection may take over from reconnection dominated by plasma effects or tearing. Further investigation of these situations is necessary.

The work described here, from many different perspectives, support the notion that turbulence is intrinsic element of fast reconnection in most astrophysical environments and that attempts to treat instabilities in reconnection systems, e.g. tearing instability, without accounting for the turbulence that these instabilities generate, are of limited relevance. At the same time, turbulent reconnection is necessary for making modern models of MHD turbulence self-consistent, allowing resolution of the magnetic knots produced by magnetic eddies, mixing matter and magnetic fields as a part of the self-similar turbulent cascade.

Furthermore, using the solar corona as an example, we have shown that a state of turbulent reconnection, with many small-scale current sheets interacting through complex flow fields, naturally arises. Even in the case of very simple laminar driving motions (such as rotation), the magnetic field naturally develops into a state filled with reconnecting current sheets and turbulent flows. The energy release in such complex fields can be determined using the idea that the plasma undergoes helicity-conserving relaxation to a minimum energy state. This has important consequences for understanding the heating the solar corona. As well as heating the plasma, the energy dissipated by magnetic reconnection may be transferred to non-thermal ions and electrons: a turbulent reconnecting plasma is an effective particle accelerator.

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## References

K. Alvelius, Random forcing of three-dimensional homogeneous turbulence. Phys. Fluids **11**, 1880–1889 (1999)

V. Archontis, F. Moreno-Insertis, K. Galsgaard, A.W. Hood, The three dimensional interaction between emerging magnetic flux and the large-scale coronal field; reconnection, current sheets and jets. Astrophys. J. **635**, 1299 (2005)

J.W. Armstrong, B.J. Rickett, S.R. Spangler, Electron density power spectrum in the local interstellar medium. Astrophys. J. **443**, 209–221 (1995)

S.A. Balbus, J.F. Hawley, Instability, turbulence, and enhanced transport in accretion disks. Rev. Mod. Phys. **70**, 1–53 (1998)

M.R. Bareford, P.K. Browning, R.A.M. Van der Linden, A nanoflare distribution generated by repeated relaxations triggered by kink instability. Astron. Astrophys. **521**, A70 (2010)

M.R. Bareford, P.K. Browning, R.A.M. Van der Linden, The flare-energy distributions generated by ensembles of kink-unstable zero-net current coronal loops. Sol. Phys. **273**, 93–115 (2011)

M.R. Bareford, A.W. Hood, P.K. Browning, Coronal heating by the partial relaxation of twisted loops. Astron. Astrophys. **550**, A40 (2013)

M. Barta, J. Buechner, M. Karlicky, Multi-scale MHD approach to the current sheet filamentation in solar coronal reconnection. Adv. Space Res. **45**, 10–17 (2010)

M. Barta, J. Buechner, M. Karlicky, J. Skala, Spontaneous current sheet fragmentation and cascading reconnection in solar flares. Astrophys. J. **737**, 24 (2011)

R. Beck, Magnetic fields in spiral arms and bars, in *Disks of Galaxies: Kinematics, Dynamics and Perturbations*, ed. by E. Athanassoula, A. Bosma, R. Mujica. ASP Conference Proceedings, vol. 275 (Astron. Soc. Pac., San Francisco, 2002), pp. 331–342. ISBN:1-58381-117-6

A. Beresnyak, On the rate of spontaneous magnetic reconnection (2013). arXiv:1301.7424

M.A. Berger, Rigorous new limits on magnetic helicity dissipation in the solar corona. Geophys. Astrophys. Fluid Dyn. **30**, 79 (1984)

M.A. Berger, M. Asgari-Targhi, Self-organised braiding and the structure of solar coronal loops. Astrophys. J. **705**, 347–355 (2009)

M.A. Berger, G.B. Field, The topological properties of magnetic helicity. J. Fluid Mech. **147**, 133 (1984)

A. Bhattacharjee, R.L. Dewar, D.A. Monticello, Energy principle with global invariants for toroidal plasma with global invariants. Phys. Rev. Lett. **45**, 347 (1980)

A. Bhattacharjee, Z.W. Ma, X. Wang, Recent developments in collisionless reconnection theory: applications to laboratory and astrophysical plasmas. Lect. Notes Phys. **614**, 351–375 (2003)

A. Bhattacharjee, Y.-M. Huang, H. Yang, B. Rogers, Fast reconnection in high-Lundquist-number plasmas due to the plasmoid instability. Phys. Plasmas **16**, 112102 (2009)

D. Biskamp, Magnetic reconnection in plasmas. Astrophys. Space Sci. **242**, 165–207 (1996)

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

M. Brown, Experimental studies of magnetic reconnection. Phys. Plasmas **6**, 1717 (1999)

M. Brown et al., Microphysics of cosmic plasmas: hierarchies of plasma instabilities from MHD to kinetic. Space Sci. Rev. (2013). doi:10.1007/s11214-013-0005-7

P.K. Browning, Helicity injection and relaxation in a solar-coronal magnetic loop with a free surface. J. Plasma Phys. **40**, 263 (1988)

P.K. Browning, E.R. Priest, Heating of coronal arcades by magnetic tearing turbulence, using the Taylor-Heyvaerts hypothesis. Astron. Astrophys. **159**, 129 (1986)

P.K. Browning, R.A.M. Van der Linden, Solar corona heating by relaxation events. Astron. Astrophys. **400**, 355 (2003)

P.K. Browning, T. Sakurai, E.R. Priest, Coronal heating in closely-packed flux tubes, a Taylor-Heyvaerts relaxation theory. Astron. Astrophys. **158**, 217 (1986)

P.K. Browning, C. Gerrard, A.W. Hood, R. Kevis, R.A.M. Van der Linden, Heating the corona by nanoflares; simulations of energy-release triggered by a kink instability. Astron. Astrophys. **485**, 837 (2008)

G. Brunetti, A. Lazarian, Acceleration of primary and secondary particles in galaxy clusters by compressible MHD turbulence: from radio haloes to gamma-rays. Mon. Not. R. Astron. Soc. **410**, 127 (2011)

J. Buechner, N. Elkina, Anomalous resistivity of current-driven isothermal plasmas due to phase-space structuring. Phys. Plasmas **13**, 082304 (2006)

T.N. Bungey, V.S. Titov, E.R. Priest, Basic topological elements of coronal magnetic fields. Astron. Astrophys. **208**, 33 (1996)

B. Burkhart, S. Stanimirović, A. Lazarian, G. Kowal, Characterizing magnetohydrodynamic turbulence in the small Magellanic cloud. Astrophys. J. **708**, 1204–1220 (2010)

P.J. Cargill, Towards ever smaller length scales. Nature **493**, 485 (2013)

P. Cargill, C. Parnell, P.K. Browning, I. de Moortel, A.W. Hood, Magnetic reconnection, from proposal to paradigm. Astron. Geophys. **51**, 3.31 (2010)

P.J. Cargill, L. Vlahos, G. Baumann, J.F. Drake, A. Nordlund, Current fragmentation and particle acceleration in solar flares. Space Sci. Rev. **173**, 223–245 (2012)

B. Chen, T.S. Bastian, S.M. White et al., Tracing electron beams in the solar corona with radio dynamic imaging spectroscopy. Astrophys. J. **763**, L21 (2013)

A. Chepurnov, A. Lazarian, Extending the big power law in the sky with turbulence spectra from Wisconsin H$\alpha$ mapper data. Astrophys. J. **710**, 853–858 (2010)

A. Chepurnov, A. Lazarian, S. Stanimirović, C. Heiles, J.E.G. Peek, Velocity spectrum for H I at high latitudes. Astrophys. J. **714**, 1398–1406 (2010)

A. Ciaravella, J.C. Raymond, The current sheet associated with the 2003 November 4 coronal mass ejection: density, temperature, thickness, and line width. Astrophys. J. **686**, 1372–1382 (2008)

J.W. Cirtain, L. Golub, A.R. Winebarger et al., Energy release in the solar corona from spatially resolved magnetic braids. Nature **493**, 501 (2013)

I.J.D. Craig, R.B. Fabling, Exact solutions for steady state, spine, and fan magnetic reconnection. Astrophys. J. **462**, 969 (1996)

R.M. Crutcher, Magnetic fields in molecular clouds: observations confront theory. Astrophys. J. **520**, 706–713 (1999)

W. Daughton, V. Roytershteyn, H. Karimabadi, Y. Yin, B.J. Albright, B. Bergen, K.J. Bowers, Role of electron physics in the development of turbulent magnetic reconnection in collisionless plasmas. Nat. Phys. **7**, 539 (2011)

E.M. de Gouveia dal Pino, A. Lazarian, Production of the large scale superluminal ejections of the microquasar GRS 1915+105 by violent magnetic reconnection. Astron. Astrophys. **441**, 845–853 (2005)

P. Demoulin, Extending the concept of separatrices to QSLs for magnetic reconnection. Space Sci. Rev. **37**, 1269 (2006). Reconnection in the Sun and at magnetospheres, eds. J. Buechner and X. Deng

A.M. Dixon, P.K. Browning, E.R. Priest, Coronal heating by relaxation in a sunspot magnetic field. Geophys. Astrophys. Fluid Dyn. **40**, 293 (1988)

A.M. Dixon, M.A. Berger, P.K. Browning, E.R. Priest, A generalisation of the Woltjer minimum energy principle. Astron. Astrophys. **225**, 156–166 (1989)

P. Dmitruk, W.H. Matthaeus, Structure of the electromagnetic field in three-dimensional Hall MHD turbulence. Phys. Plasmas **13**, 042307 (2006)

J.F. Drake, M. Swisdak, H. Che, M.A. Shay, Electron acceleration from contracting magnetic islands during reconnection. Nature **443**, 553–556 (2006)

J.F. Drake, M. Opher, M. Swisdak, J.N. Chamoun, A magnetic reconnection mechanism for the generation of anomalous cosmic rays. Astrophys. J. **709**, 963–974 (2010)

B.G. Elmegreen, J. Scalo, Interstellar turbulence I: observations and processes. Annu. Rev. Astron. Astrophys. **42**, 211–273 (2004)
G.L. Eyink, A. Lazarian, E.T. Vishniac, Fast magnetic reconnection and spontaneous stochasticity. Astrophys. J. **743**, 51 (2011)
E.L. Eyink, E. Vishniac, C. Lalescu et al., Flux freezing breakdown in high conductivity MHD turbulence. Nature **497**, 466 (2013)
J.M. Finn, T.M. Antonsen, Magnetic helicity, what is it and what is it good for? Commun. Plasma Phys. Control. Fusion **9**, 111 (1985)
R. Fitzpatrick, Scaling of forced magnetic reconnection in the Hall-magnetohydrodynamic Taylor problem. Phys. Plasmas **11**, 937–946 (2004)
T.G. Forbes, The nature of Petschek-type reconnection. Earth Planets Space **53**, 423 (2001)
H.P. Furth, J. Killeen, M.N. Rosenbluth, Finite resistivity instabilities of a sheet pinch. Phys. Fluids **6**, 459 (1963)
B.M. Gaensler, M. Haverkorn, B. Burkhart, K.J. Newton-McGee, R.D. Ekers, A. Lazarian, N.M. McClure-Griffiths, T. Robishaw, J.M. Dickey, A.J. Green, Low-Mach-number turbulence in interstellar gas revealed by radio polarization gradients. Nature **478**, 214–217 (2011)
P. Goldreich, S. Sridhar, Toward a theory of interstellar turbulence. 2: strong Alfvenic turbulence. Astrophys. J. **438**, 763–775 (1995). (GS95)
M. Gordovskyy, P.K. Browning, Particle acceleration by magnetic reconnection in a twisted coronal loop. Astrophys. J. **729**, 101 (2011)
M. Gordovskyy, P.K. Browning, High energy particles in confined solar flares: acceleration in reconnecting unstable twisted coronal loops. Sol. Phys. **277**, 299 (2012)
M. Gordovskyy, P.K. Browning, G.E. Vekstein, Particle acceleration in a transient magnetic reconnection event. Astron. Astrophys. **51**, A21 (2010a)
M. Gordovskyy, P.K. Browning, G.E. Vekstein, Particle acceleration in a fragmenting periodic reconnecting current sheets in solar flares. Astrophys. J. **720**, 1603 (2010b)
M. Gordovskyy, P.K. Browning, N. Bian, E. Kontar, Effects of collisions and magnetic convergence on high energy particles in solar coronal loops. Sol. Phys. **284**, 489–498 (2013a)
M. Gordovskyy, P.K. Browning, N. Bian, E. Kontar, Acceleration and transport of energetic flare particles in an unstable twisted loop in a gravitationally-stratified atmosphere. Astron. Astrophys. (2013b, in press)
Z.B. Gao, P.H. Diamond, X.G. Wong, Magnetic reconnection, helicity-dynamics and hyperdiffusion. Astrophys. J. **757**, 173 (2012)
T.S. Hahm, R.M. Kulsrud, Forced magnetic reconnection. Phys. Fluids **28**, 2412–2418 (1985)
J. Heyvaerts, E.R. Priest, Coronal heating by reconnection in DC current systems; a theory based on Taylor hypothesis. Astron. Astrophys. **137**, 63 (1984)
A.W. Hood, P.K. Browning, R.A.M. Van der Linden, Coronal heating by magnetic reconnection in loops with zero-net current. Astron. Astrophys. **506**, 913 (2009)
Y.-M. Huang, A. Bhattarcharjee, Plasmoid instability in high-Lundquist-number magnetic reconnection. Phys. Plasmas **20**, 055702 (2013)
A.R. Jacobson, R.W. Moses, Nonlocal dc electrical conductivity of a Lorentz plasma in a stochastic magnetic field. Phys. Rev. A **29**, 3335–3342 (1984)
R. Jain, P.K. Browning, K. Kusano, Solar coronal heating by forced magnetic reconnection; multiple reconnection events. Phys. Plasmas **12**, 012904 (2005)
T.R. Jarboe, Review of spheromak research. Plasma Phys. Control. Fusion **36**, 945 (1994)
H. Karimabadi, V. Roytershteyn, M. Wan, W.H. Matthaeus, W. Daughton et al., Coherent structures, intermittent turbulence, and dissipation in high-temperature plasmas. Phys. Plasmas **20**, 012303 (2013)
M. Karlicky, M. Barta, D. Nickeler, Fragmentation during merging of plasmoids in the magnetic field reconnection. Astron. Astrophys. **541**, A86 (2012)
E.-j. Kim, P.H. Diamond, On turbulent reconnection. Astrophys. J. **556**, 1052–1065 (2001)
B. Kliem, Particle orbits, trapping and acceleration in a filamentary current sheet model. Astrophys. J. **90**, 719 (1994)
K. Kotera, A.V. Olinto, The astrophysics of ultrahigh-energy cosmic rays. Annu. Rev. Astron. Astrophys. **49**, 119–153 (2011)
G. Kowal, A. Lazarian, E.T. Vishniac, K. Otmianowska-Mazur, Numerical tests of fast reconnection in weakly stochastic magnetic fields. Astrophys. J. **700**, 63–85 (2009)
G. Kowal, E.M. de Gouveia Dal Pino, A. Lazarian, Magnetohydrodynamic simulations of reconnection and particle acceleration: three-dimensional effects. Astrophys. J. **735**, 102 (2011)
G. Kowal, A. Lazarian, E.T. Vishniac, K. Otmianowska-Mazur, Reconnection studies under different types of turbulence driving. Nonlinear Process. Geophys. **19**, 297–314 (2012a)
G. Kowal, E.M. de Gouveia Dal Pino, A. Lazarian, Acceleration in turbulence and weakly stochastic reconnection. Phys. Rev. Lett. **108**, 241102 (2012b)

K. Kusano, Y. Suzuki, H. Kubo, T. Miyoshi, K. Nishikawa, 3D simulation study of the MHD relaxation process in the solar corona. Astrophys. J. **433**, 361 (1994)
A. Lazarian, Astrophysical implications of turbulent reconnection: from cosmic rays to star formation, in *Magnetic Fields in the Universe: From Laboratory and Stars to Primordial Structures*, vol. 784 (AIP, New York, 2005), p. 42
A. Lazarian, Theoretical approaches to particle propagation and acceleration in turbulent intergalactic medium. Astron. Nachr. **327**, 609 (2006)
A. Lazarian, Obtaining spectra of turbulent velocity from observations. Space Sci. Rev. **143**, 357–385 (2009)
A. Lazarian, J. Cho, Scaling, intermittency and decay of MHD turbulence. Phys. Scr. T **116**, 32 (2005)
A. Lazarian, M. Opher, A model of acceleration of anomalous cosmic rays by reconnection in the heliosheath. Astrophys. J. **703**, 8 (2009)
A. Lazarian, D. Pogosyan, Velocity modification of HI spectrum and clouds in velocity space. Bull. Am. Astron. Soc. **31**, 1449 (1999)
A. Lazarian, E.T. Vishniac, Reconnection in a weakly stochastic field. Astrophys. J. **517**, 700–718 (1999). (LV99)
A. Lazarian, E.T. Vishniac, Model of reconnection of weakly stochastic magnetic field and its implications. Rev. Mex. Astron. Astrofís., Ser. Conf. **36**, 81–88 (2009)
A. Lazarian, H. Yan, Magnetic reconnection in turbulent plasmas and gamma ray bursts. AIP Conf. Ser. **1505**, 101 (2012)
A. Lazarian, V. Petrosian, H. Yan, J. Cho, Physics of gamma-ray bursts: turbulence, energy transfer and reconnection (2003). arXiv:astro-ph/0301181
A. Lazarian, E.T. Vishniac, J. Cho, Magnetic field structure and stochastic reconnection in a partially ionized gas. Astrophys. J. **603**, 180–197 (2004)
A. Lazarian, A. Esquivel, R. Crutcher, Magnetisation of cloud cores and envelopes and other consequences of reconnection diffusion. Astrophys. J. **757**, 154 (2012a)
A. Lazarian, L. Vlahos, G. Kowal, H. Lan, A. Beresnyak, E. del Pino, Turbulence, magnetic reconnection in turbulent fluids and energetic particle acceleration. Space Sci. Rev. **173**, 107 (2012b)
Y. Li, J. Lin, Acceleration of electrons and protons in reconnecting current sheets including single or multiple X-points. Sol. Phys. **279**, 91 (2012)
D.W. Longcope, S.C. Cowley, Current sheet formation along three-dimensional magnetic separators. Phys. Plasmas **3**, 2885 (1996)
R.M. Lothian, P.K. Browning, Energy dissipation and helicity in coronal loops of variable cross-section. Sol. Phys. **161**, 289 (1995)
R.M. Lothian, P.K. Browning, Energy dissipation and helicity in coronal loops of variable cross-section. Sol. Phys. **194**, 205–227 (2000)
N.F. Loureiro, D.A. Uzdensky, A.A. Schekochihin, S.C. Cowley, T.A. Yousef, Turbulent magnetic reconnection in two dimensions. Mon. Not. R. Astron. Soc. **399**, L146–L150 (2009)
N.F. Loureiro, T. Samataney, A.A. Schekochihin, D.A. Uzdensky, Magnetic reconnection and stochastic plasmoid chains in high-Lundquist-number plasmas. Phys. Plasmas **19**, 042303 (2012)
B.C. Low, Spontaneous current sheets in an ideal hydromagnetic fluid. Astrophys. J. **649**, 1064 (2006)
R.S. Maclean, J. Buechner, E.R. Priest, Relationship between the topological skeleton, current concentrations, and 3D magnetic reconnection sites in the solar atmosphere. Astron. Astrophys. **501**, 321–333 (2009)
S. Markidis, P. Henri, G. Lapenta, A. Divin, M. Goldman, D. Newman, E. Laure, Kinetic simulations of plasmoid chain dynamics. Phys. Plasmas **20**, 082105 (2012)
W.H. Matthaeus, S.L. Lamkin, Rapid magnetic reconnection caused by finite amplitude fluctuations. Phys. Fluids **28**, 303–307 (1985)
W.H. Matthaeus, S.L. Lamkin, Turbulent magnetic reconnection. Phys. Fluids **29**, 2513–2534 (1986)
D.B. Melrose, Acceleration mechanisms (2009). arXiv:0902.1803
J.A. Miller, P.J. Cargill, A.G. Emslie et al., Critical issues for understanding particle acceleration in impulsive solar flares. J. Geophys. Res. **103**, 14631–14659 (1997)
H.K. Moffat, *Magnetic Field Generation in Electrically Conducting Fluids* (Cambridge University Press, London, 1978)
D. Nandy, M. Hahn, R.C. Canfield, D.W. Longcope, Detection of a Taylor-like plasma relaxation process in the Sun. Astrophys. J. **597**, L73–L76 (2003)
C.S. Ng, S. Lin, A. Bhattarcharjee, High Lundquist number scaling in three-dimensional simulations of Parker's model of coronal heating. Astrophys. J. **747**, 109 (2012)
Y. Ono, H. Tanabe, T. Yamada et al., Ion and electron heating characteristics of magnetic reconnection in tokamak plasma merging experiments. Plasma Phys. Control. Fusion **54**, 12409 (2012)
M. Onofri, L. Primavera, F. Malara, P. Veltri, Three-dimensional simulations of magnetic reconnection in slab geometry. Phys. Plasmas **11**, 4837 (2004)

P. Padoan, M. Juvela, A. Kritsuk, M.L. Norman, The power spectrum of supersonic turbulence in Perseus. Astrophys. J. Lett. **653**, L125–L128 (2006)
P. Padoan, M. Juvela, A. Kritsuk, M.L. Norman, The power spectrum of turbulence in NGC 1333: outflows or large-scale driving? Astrophys. J. Lett. **707**, L153–L157 (2009)
E.N. Parker, Sweet's mechanism for merging magnetic fields in conducting fluids. J. Geophys. Res. **62**, 509–520 (1957)
E.N. Parker, Topological dissipation and small-scale magnetic fields in turbulent gases. Astrophys. J. **174**, 499 (1972)
E.N. Parker, Comments on the reconnexion rate of magnetic fields. J. Plasma Phys. **9**, 49 (1973)
E.N. Parker, Nanoflares and the solar X-ray corona. Astrophys. J. **330**, 474 (1988)
E.N. Parker, Fast dynamos, cosmic rays, and the galactic magnetic field. Astrophys. J. **401**, 137–145 (1992)
C. Parnell, A.J. Haynes, K. Galsgaard, Recursive reconnection and magnetic skeletons. Astrophys. J. **675**, 1656 (2008)
C. Parnell, R.C. Maclean, A. Haynes, The detection of numerous magnetic separators in a 3D simulation of emerging magnetic flux. Astrophys. J. Lett. **725**, L214 (2010)
P. Petkaki, M.P. Freeman, T. Kirk, C.E.J. Watt, R.B. Horne, Anomalous resistivity and the nonlinear evolution of the ion-acoustic instability. J. Geophys. Res. **11**, A01205 (2006)
H.E. Petschek, Magnetic field annihilation. NASA Spec. Publ. **50**, 425–439 (1964)
G.W. Pneuman, Two-ribbon flares—post-flare loops, in *Solar Flare Magnetohydrodynamics* (1981), pp. 379–428
D.I. Pontin, Three-dimensional magnetic reconnection regimes; a review. Adv. Space Res. **47**, 158 (2011)
D.I. Pontin, G. Hornig, E.R. Priest, Kinematic reconnection at a magnetic null point: fan-aligned current. Geophys. Astrophys. Fluid Dyn. **99**, 77 (2005)
D.I. Pontin, A.L. Wilmot-Smith, G. Hornig, K. Galsgaard, Dynamics of braided coronal loops. Cascade to multiple small-scale reconnection events. Astron. Astrophys. **525**, A57 (2011)
E.R. Priest, T. Forbes, *Magnetic Reconnection* (Cambridge University Press, Cambridge, 2000)
E.R. Priest, T. Forbes, The magnetic nature of solar flares. Astron. Astrophys. Rev. **10**, 313–377 (2002)
E.R. Priest, V.S. Titov, Magnetic reconnection at three-dimensional null points. Philos. Trans. R. Soc. Lond. A **354**, 2951–2992 (1996)
E.R. Priest, J. Heyvaerts, A.M. Title, A flux-tube tectonics model for solar coronal heating driven by the magnetic carpet. Astrophys. J. **576**, 533 (2002)
E.R. Priest, D. Pontin, G. Hornig, On the nature of three-dimensional magnetic reconnection. J. Geophys. Res. **108**(A7), 1285 (2003)
A.F. Rapazzo, M. Velli, G. Einaudi, R.B. Dahlburg, Coronal heating, weak MHD turbulence and scaling laws. Astrophys. J. **657**, L47 (2007)
A.F. Rapazzo, M. Velli, G. Einaudi, Fieldlines twisting in a noisy corona: implications for energy storage and release, and initiation of solar eruptions. Astrophys. J. **771**, 76 (2013)
M.G. Rusbridge, Model of field reversal in diffuse pinch. Plasma Phys. Control. Fusion **19**, 499 (1977)
M.G. Rusbridge, The relationship between the tangled discharge and dynamo models of magnetic relaxation. Plasma Phys. Control. Fusion **33**, 1381 (1991)
R. Santos-Lima, A. Lazarian, E.M. de Gouveia Dal Pino, J. Cho, Diffusion of magnetic field and removal of magnetic flux from clouds via turbulent reconnection. Astrophys. J. **714**, 442–461 (2010)
R. Schlickeiser, I. Lerche, Cosmic gas dynamics. I—Basic equations and the dynamics of hot interstellar matter. Astron. Astrophys. **151**, 151–156 (1985)
M. Scholer, Undriven magnetic reconnection in an isolated current sheet. J. Geophys. Res. **94**, 8805–8812 (1989)
S. Servidio, W.H. Matthaeus, M.A. Shay, P. Dmitruk, P.A. Cassak, M. Wan, Statistics of magnetic reconnection in two-dimensional magnetohydrodynamic turbulence. Phys. Plasmas **17**, 032315 (2010)
M.A. Shay, J.F. Drake, R.E. Denton, D. Biskamp, Structure of the dissipation region during collisionless magnetic reconnection. J. Geophys. Res. **103**, 9165–9176 (1998)
M.A. Shay, J.F. Drake, M. Swisdak, B.N. Rogers, The scaling of embedded collisionless reconnection. Phys. Plasmas **11**, 2199–2213 (2004)
K. Shibata, T. Magara, Solar flares: magnetohydrodynamic processes. Living Rev. Sol. Phys. **8**, 6 (2011)
K. Shibata, S. Tanuma, Plasmoid-induced-reconnection and fractal reconnection. Earth Planets Space **53**, 473–482 (2001)
K. Schindler, M. Hesse, J. Birn, General magnetic reconnection, parallel electric fields and helicity. J. Geophys. Res. **93**, 5547 (1988)
S. Servidio, P. Dmitruk, A. Greco, M. Wan, S. Donato, P.A. Cassak, M. Shay, V. Carbone, W.H. Matthaeus, Magnetic reconnection as an element of turbulence. Nonlinear Process. Geophys. **18**, 675–695 (2011)
D. Smith, S. Ghosh, P. Dmitruk, W.H. Matthaeus, Hall and turbulence effects on magnetic reconnection. Geophys. Res. Lett. **310**, L02805 (2004)

T.W. Speiser, Conductivity without collisions or noise. Planet. Space Sci. **18**, 613 (1970)
A. Stanier, P.K. Browning, M. Gordovskyy, K.G. McClements, M.P. Gryazenevich, V.S. Lukin, Two-fluid simulations of driven reconnection in the Mega Ampere Spherical Tokamak. Phys. Plasmas (2013, submitted). arXiv:1308.2855
S. Stanimirović, A. Lazarian, Velocity and density spectra of the small Magellanic cloud. Astrophys. J. Lett. **551**, L53–L56 (2001)
P.A. Sweet, The neutral point theory of solar flares, in *Electromagnetic Phenomena in Cosmical Physics*, ed. by B. Lehnert. Conf. Proc. IAU Symposium, vol. 6 (Cambridge University Press, Cambridge, 1958), pp. 123–134
R. Sych, V.M. Nakariakov, M. Karlicky, S. Anfinogentov, Relationship between wave processes in sunspots and quasi-periodic pulsations in active region flares. Astron. Astrophys. **505**, 791–799 (2009)
S. Tanuma, T. Yokoyama, T. Kudoh, K. Shibata, 2D MHD numerical simulations of magnetic reconnection generated by a supernova shock in the interstellar medium: generation of X-ray gas in a galaxy. Astrophys. J. **551**, 312–332 (2001)
J.B. Taylor, Relaxation of toroidal plasma and generation of reverse magnetic fields. Phys. Rev. Lett. **33**, 1139–1142 (1974)
J.B. Taylor, Relaxation and magnetic reconnection in plasmas. Rev. Mod. Phys. **58**, 741–763 (1986)
V.S. Titov, G. Hornig, P. Demoulin, Theory of magnetic connectivity in the solar corona. J. Geophys. Res. (2002)
R. Turkmani, P.J. Cargill, K. Galsgaard, L. Vlahos, H. Isliker, Particle acceleration in stochastic current sheets in stressed coronal active regions. Astron. Astrophys. **449**, 749 (2006)
M. Ugai, Computer studies on development of the fast reconnection mechanism for different resistivity models. Phys. Fluids B **4**, 2953–2963 (1992)
M. Ugai, T. Tsuda, Magnetic field-line reconnexion by localized enhancement of resistivity. I—Evolution in a compressible MHD fluid. J. Plasma Phys. **17**, 337–356 (1977)
D.A. Uzdensky, The fast collisionless reconnection condition and the self-organization of solar coronal heating. Astrophys. J. **671**, 2139 (2007)
D.A. Uzdensky, N.F. Loureiro, A.A. Schekochhin, Fast magnetic reconnection in the plasmoid-dominated regime. Phys. Rev. Lett. **105**, 23 (2010)
J.P. Vallée, Observations of the magnetic fields inside and outside the Milky Way, starting with globules ($\sim 1$ parsec), filaments, clouds, superbubbles, spiral arms, galaxies, superclusters, and ending with the cosmological universe's background surface (at $\sim 8$ teraparsecs). Fundam. Cosm. Phys. **19**, 1–89 (1997)
J.P. Vallée, Observations of the magnetic fields inside and outside the solar system: from meteorites ($\sim$ 10 attoparsecs). Asteroids, planets, stars, pulsars, masers to protostellar cloudlets ($< 1$ parsec). Fundam. Cosm. Phys. **19**, 319–422 (1998)
A.A. Van Ballegoijen, Electric currents in the solar corona and the existence of magnetostatic equilibrium. Astrophys. J. **298**, 421 (1985)
G.E. Vekstein, R. Jain, Energy release and plasma heating by forced magnetic reconnection. Phys. Plasmas **5**, 1506 (1998)
G.E. Vekstein, E.R. Priest, C.D.C. Steele, MHD equilibria and cusp formation at an X-type neutral line by footpoint shearing. Astrophys. J. **384**, 333 (1992)
G.E. Vekstein, E.R. Priest, C.D.C. Steele, On the problem of magnetic coronal heating by turbulent relaxation. Astrophys. J. **417**, 781 (1993)
E. Vishniac, A. Lazarian, Reconnection in the interstellar medium. Astrophys. J. **591**, 193 (1999)
L. Vlahos, H. Isliker, F. Lepreti, Particle acceleration in an evolving network of unstable current sheets. Astrophys. J. **608**, 540 (2004)
L. Vlahos, S. Krucker, P.J. Cargill, The solar flare, a strongly turbulent particle accelerator, in *Turbulence in Space Plasmas*, ed. by L. Vlahos, P.J. Cargill (Springer, Berlin, 2009)
X. Wang, A. Bhattacharjee, Z.W. Ma, Scaling of collisionless forced reconnection. Phys. Rev. Lett. **87**, 265003 (2001)
P.G. Watson, S. Oughton, I.J.D. Craig, The impact of small-scale turbulence on laminar magnetic reconnection. Phys. Plasmas **14**, 032301 (2007)
A.L. Wilmot-Smith, D. Pontin, G. Hornig, Dynamics of braided coronal loops. I. Onset of magnetic reconnection. Astron. Astrophys. **516**, A5 (2010)
R. Wolfson, G.E. Vekstein, E.R. Priest, Nonlinear evolution of the coronal magnetic field under reconnective relaxation. Astrophys. J. **428**, 345 (1994)
M. Yamada, Progress in understanding magnetic reconnection in laboratory and space astrophysical plasmas. Phys. Plasmas **14**, 058102 (2007)
M. Yamada, Y. Ono, M. Hayakawa, K. Katsurai, F.W. Perkins, Magnetic reconnection in plasma toroids with cohelicity and counterhelicity. Phys. Rev. Lett. **55**, 721–725 (1990)
M. Yamada, R. Kulsrud, H. Ji, Magnetic reconnection. Rev. Mod. Phys. **86**, 603–664 (2011)

M. Yan, L.C. Lee, E.R. Priest, Fast magnetic reconnection with small shock angles. J. Geophys. Res. **97**, 8277–8293 (1992)
A.R. Yeates, G. Hornig, A.L. Wilmot-Smith, Topological constraints on magnetic relaxation. Phys. Rev. Lett. **105**, 085002 (2010)
G. Zank, W.H. Matthaeus, Nearly incompressible fluids II: magnetohydrodynamics, turbulence and waves. Phys. Fluids A **5**, 257 (1993)
B. Zhang, H. Yan, The internal-collision-induced magnetic reconnection and turbulence (ICMART) model of gamma-ray bursts. Astrophys. J. **726**, 90 (2011)
V. Zharkova et al., Recent advances in understanding particle acceleration processes in solar flares. Space Sci. Rev. **159**, 357–420 (2011)
E.G. Zweibel, M. Yamada, Magnetic reconnection in astrophysical and laboratory plasmas. Annu. Rev. Astron. Astrophys. **47**, 291–332 (2009)