Astrophysical Implications of Turbulent Reconnection: from cosmic rays to star formation

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Abstract. Turbulent reconnection allows fast magnetic reconnection of astrophysical magnetic fields. This entails numerous astrophysical implications and opens new ways to approach long standing problems. I briefly discuss a model of turbulent reconnection within which the stochasticity of 3D magnetic field enables rapid reconnection through both allowing multiple reconnection events to take place simultaneously and by restricting the extension of current sheets. In fully ionized gas the model in Lazarian & Vishniac 99 predicts reconnection rates that depend only on the intensity of turbulence. In partially ionized gas a modification of the original model in Lazarian, Vishniac & Cho 04 predicts the reconnection rates that, apart from the turbulence intensity depend on the degree of ionization. In both cases the reconnection may be slow and fast depending on the level of turbulence in the system. As the result, the reconnection gets bursty, which provides a possible explanation to Solar flares and possibly to gamma ray busts. The implications of the turbulent reconnection model have not been yet studied in sufficient detail. I discuss first order Fermi acceleration of cosmic ray that takes place as the oppositely directed magnetic fluxes move together. This acceleration would work in conjunction with the second order Fermi acceleration that is caused by turbulence in the reconnection region. In partially ionized gas the stochastic reconnection enables fast removal of magnetic flux from star forming molecular clouds.

WHAT IS MAGNETIC RECONNECTION?

Magnetic fields play key role for many Astrophysical processes like star formation, cosmic ray transport and acceleration, accretion etc. As a rule, magnetic diffusivity is slow over huge astrophysical scales and therefore frozenness of magnetic field provides an excellent approximation (see Moffatt 1978). Magnetic field lines in astrophysical highly conducting fluids act as elastic threads that are moved together with the fluid. However, fluid motions are likely to create knots in which magnetic threads will be pressing against each other. If the state of frozenness is not violated at these knots this would result in the formation of felt or Jello-like structure of magnetic field that is favored by some astrophysicists (Cox 2004). If, however, crossing magnetic field lines can change their topology, the dynamics of magnetized fluid is completely different.

The situation is rather dramatic. In fact, we cannot claim that we understand the dynamics of magnetized astrophysical fluids if we cannot figure out what picture is correct, i.e. whether astrophysical fluids act as a magnetic Jello or have fluid type behavior (see more below). Note, that adopting the first alternative would also mean kiss of death to the contemporary dynamo theories, i.e. to the theories that explain magnetism
of different astrophysical objects from stars to galaxies by appealing to the amplification of magnetic fields by fluid motions (see Parker 1979).

A naive answer to the question of whether astrophysical magnetic field can change the topology is positive. Indeed, as oppositely directed magnetic fields come together the diffusion of magnetic field gets important inducing changes of magnetic topology. The issue is the rates at which this topology can change. And this is the key issue around which many decades of controversy about fast reconnection are centered (see Biskamp 2000, Priest and Forbes 2000).

The most natural and robust scheme which was suggested first in the literature is the well known Sweet-Parker model of reconnection (Parker 1957, Sweet 1958). Illustrated in Figure 1 this model of reconnection has two oppositely directed magnetic fluxes that get into contact over a scale $L$. While for most of the volume the magnetic field lines are frozen in, the magnetic diffusivity is important within the current sheet of thickness $\Delta$ (see Fig. 1). The local velocity at which the change of magnetic topology takes place,
i.e. the reconnection velocity \( V_R \), is given by

\[
V_R = \frac{\eta}{\Delta},
\]

(1)

where \( \eta \) is the resistivity coefficient\(^1\). One may notice that the local reconnection velocity can be arbitrary large provided that \( \Delta \) is sufficiently small. However, if we are interested in reconnecting sufficient amounts of magnetic flux we should consider steady state reconnection. Such a reconnection requires that the fluid and shared flux\(^2\) be removed from the reconnection region in order to allow fresh oppositely directed magnetic field lines to get into close contact. This imposes the *global* constraint upon the reconnection rate:

\[
V_R L = V_A \Delta,
\]

(2)

where the removal of fluid happens with the Alfvén velocity \( V_A \) and the thickness of the outflow is determined by \( \Delta \). As the result of these two constraints acting simultaneously we get the well-known Sweet-Parker reconnection rate:

\[
V_R = V_A R_L^{-1/2},
\]

(3)

where \( R_L \equiv (LV_A/\eta) \) is the so-called Lundquist number, which is an analog of the hydrodynamic Reynolds number. The enormous scales of astrophysical systems, i.e. large \( L \) and relatively low values of magnetic diffusivity \( \eta \) make \( R_L \) really huge for most of astrophysically interesting situations. Indeed, the corresponding \( R_L \) may range from \( 10^{10} \) to \( 10^{20} \) for interstellar gas. As the result the reconnection rates get so insignificant that one should conclude that forgetting about reconnection *if it happens with the Sweet-Parker rate* is an excellent astrophysical approximation. This entails many interesting conclusions. One of them is that all current magnetohydrodynamic simulations are useless, as the present day computer codes are diffusive and do not describe Jello-type fluids. On the contrary, they induce efficient magnetic reconnection allowing magnetic field to change its topology on dynamical times.

Is the situation that bad? How can one explain Solar flares, which indicate that the real world astrophysical magnetic fields do change their topology over short time scales (see Dere 1996)?

The problem of the Sweet-Parker reconnection scheme is a huge disparity of scales as \( L \) is an astrophysical scale, while \( \Delta \) is given by microphysics. The attempts to remove this disparity resulted in Petscheck (1964) scheme of reconnection (see Fig. 1, left panel). In this model the both scales involved are determined by microphysics. The reconnection happens over tiny portion of the length of magnetic field lines, while the rest of the magnetic flux forms an X-type configuration that allows an easy escape of the reconnected flux and fluid.

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\(^1\) The coefficient of magnetic field diffusivity in a fully ionized plasma is \( \eta = c^2/(4\pi \sigma) \approx 10^{13}T^{-3/2} \text{ cm}^2 \text{ s}^{-1} \), where \( \sigma \approx 10^{7}T^{3/2} \text{ s}^{-1} \) is the plasma conductivity and \( T \) is electron temperature measured in Kelvins. The characteristic time for field diffusion through a plasma slab of size \( y \) is \( y^2/\eta \), which is large for any “astrophysical” \( y \).

\(^2\) It is easy to generalize the idealised 2D picture above to three dimensions. In 3D the current flows along the shared magnetic flux. This flux is being ejected together with the fluid from the diffusion region.
Formally, the Sweet-Parker scheme and the Petscheck scheme are of the same class of the reconnection models in which the local and global reconnection rate must coincide. This imposes stringent constraints on the geometry of the Petscheck model. Indeed, the inevitable requirement of Petscheck scheme is that X-type structure must be sustainable over the scale at which opposite fluxes get together. If external forcing decreases X-type opening, the global outflow conditions cannot be satisfied and the reconnection is choked. Surely, the reconnection can happen fast over short time scales, but for reconnecting large amounts of flux a quasi-steady fast reconnection is required. This means that, for instance, interstellar magnetic fields should be configured to form X-points over many parsecs to enable fast reconnection.

Petscheck scheme has been surrounded by many controversies from the time that it originated. It is clear at this moment that it cannot be sustained at large $R_L$ for smooth resistivities. Whether or not anomalous effects, e.g. those related to Hall term, can provide reconnection at rates comparable with the Alfvén speed is hotly debated\(^3\) (see Biskamp, Schwarz & Drake 1997, Shay et al. 1998, Shay & Drake 1998, Bhattacharjee, Ma & Wang 2001). We feel, however, that the issue of satisfying boundary outflow conditions is the most controversial element in applying Petscheck scheme to astrophysical conditions. If very special global geometry or magnetic fluxes, e.g. convex magnetized regions, is required to enable reconnection, then for a generic astrophysical case the reconnection is slow.

**HOW CAN TURBULENCE ENHANCE RECONNECTION?**

Reconnection involves dissipation and diffusion. Therefore it is natural to wonder whether turbulence can enhance the reconnection rate. The notion that magnetic field stochasticity might affect current sheet structures is not unprecedented. In earlier work Speiser (1970) showed that in collisionless plasmas the electron collision time should be replaced with the time a typical electron is retained in the current sheet. Also Jacobson & Moses (1984) proposed that current diffusivity should be modified to include diffusion of electrons across the mean field due to small scale stochasticity. These effects will usually be small compared to effect of a broad outflow zone containing both plasma and ejected shared magnetic flux. Moreover, while both of these effects will affect reconnection rates\(^4\), they are not sufficient to produce reconnection speeds comparable to the Alfvén speed in most astrophysical environments.

"Hyper-resistivity" discussed in a number of works (e.g. Strauss 1985, Bhattacharjee & Hameiri 1986, Hameiri & Bhattacharjee 1987) is a more subtle attempt to derive fast reconnection from turbulence within the context of mean-field resistive MHD. The

\(^3\) For instance, the necessary condition for the anomalous effects to be important, e.g. for that the electron mean free path is less than the current sheet thickness (see Trintchouk et al. 2003) is difficult to satisfy for the ISM, where the Sweet-Parker current sheet thickness is typically much larger than the ion Larmor radius.

\(^4\) It looks that current experiments to study reconnection do measure such enhancements related to magnetic field stochasticity (Ji 2005).
form of the parallel electric field can be derived from magnetic helicity conservation. Integrating by parts one obtains a term which looks like an effective resistivity proportional to the magnetic helicity current. There are several assumptions implicit in this derivation, but the most important problem is that by adopting a mean-field approximation one is already assuming some sort of small-scale smearing effect, equivalent to fast reconnection. Strauss (1988) partially circumvented this problem by examining the effect of tearing mode instabilities within current sheets. However, the resulting reconnection speed enhancement is roughly what one would expect based simply on the broadening of the current sheets due to internal mixing. This effect does not allow us to evade the constraints on the global plasma flow that lead to slow reconnection speeds, a point which has been demonstrated numerically (Matthaeus & Lampkin 1985) and analytically (LV99).

A different approach has been adopted in Lazarian & Vishniac (1999, henceforth LV99). The starting point there is that turbulence is a generic state of astrophysical fluids (see Armstrong, Rickett, Spangler 1995, Lazarian & Pogosyan 2004, Lazarian 2004). MHD turbulence guarantees the presence of a stochastic field component, although its amplitude and structure clearly depends on the model we adopt for MHD turbulence (see review by Cho, Lazarian & Vishniac 2003a and references therein), as well as the specific environment of the field. We consider the case in which there exists a large scale, well-ordered magnetic field, of the kind that is normally used as a starting point for discussions of reconnection. In addition, we expect that the field has some small scale ‘wandering’ of the field lines. On any given scale the typical angle by which field lines differ from their neighbors is \( \phi \ll 1 \), and this angle persists for a distance along the field lines \( \lambda_\parallel \) with a correlation distance \( \lambda_\perp \) across field lines (see Fig. 1).

The modification of the global constraint induced by mass conservation in the presence of a stochastic magnetic field component is self-evident. Instead of being squeezed from a layer whose width is determined by Ohmic diffusion, the plasma may diffuse through a much broader layer, \( L_y \sim \langle y^2 \rangle^{1/2} \) (see Fig. 1), determined by the diffusion of magnetic field lines. This suggests an upper limit on the reconnection speed of \( \sim V_A \langle y^2 \rangle^{1/2} / L_x \). This will be the actual speed of reconnection if the progress of reconnection in the current sheet does not impose a smaller limit. The value of \( \langle y^2 \rangle^{1/2} \) can be determined once a particular model of turbulence is adopted, but it is obvious from the very beginning that this value is determined by field wandering rather than Ohmic diffusion as in the Sweet-Parker case.

What about limits on the speed of reconnection that arise from considering the structure of the current sheet? In the presence of a stochastic field component, magnetic reconnection dissipates field lines not over their entire length \( \sim L_x \), but only over a scale \( \lambda_\parallel \ll L_x \) (see Fig. 1), which is the scale over which magnetic field line deviates from its original direction by the thickness of the Ohmic diffusion layer \( \lambda_\perp^{-1} \approx \eta / V_{rec,\text{local}} \). If the angle \( \phi \) of field deviation does not depend on the scale, the local reconnection velocity would be \( \sim V_A \phi \) and would not depend on resistivity. In LV99 we claimed that \( \phi \) does depend on scale. Therefore the local reconnection rate \( V_{rec,\text{local}} \) is given by the usual Sweet-Parker formula but with \( \lambda_\parallel \) instead of \( L_x \), i.e. \( V_{rec,\text{local}} \approx V_A (V_A \lambda_\parallel / \eta)^{-1/2} \). It is obvious from Fig. 1 that \( \sim L_x / \lambda_\parallel \) magnetic field lines will undergo reconnection simultaneously (compared to a one by one line reconnection process for the Sweet-
Parker scheme). Therefore the overall reconnection rate may be as large as $V_{\text{rec.global}} \approx V_A(L_x/\lambda_\parallel)(V_A\lambda_\parallel/\eta)^{-1/2}$. Whether or not this limit is important depends on the value of $\lambda_\parallel$.

The relevant values of $\lambda_\parallel$ and $(\langle y^2 \rangle)^{1/2}$ depend on the magnetic field statistics. This calculation was performed in LV99 using the Goldreich-Sridhar (1995, henceforth) model of MHD turbulence, which has been supported by numerical simulations (see review by Cho, Lazarian & Vishniac 2003z and references therein). For instance, for the GS95 spectrum, which according to Cho & Lazarian (2003) persists for Alfvénic mode even in compressible MHD turbulence with a large-scale high-amplitude driving, the upper limit on the reconnection speed was

$$V_{r,\text{up}} = V_A \min \left[ \left( \frac{L_x}{l} \right)^{1/2} \left( \frac{l}{L_x} \right)^{1/2} \right] \left( \frac{v_l}{V_A} \right)^2,$$

where $l$ and $v_l$ are the energy injection scale and turbulent velocity at this scale respectively. In LV99 other processes that can impede reconnection were found to be less restrictive. For instance, the tangle of reconnection field lines crossing the current sheet will need to reconnect repeatedly before individual flux elements can leave the current sheet behind. The rate at which this occurs can be estimated by assuming that it constitutes the real bottleneck in reconnection events, and then analyzing each flux element reconnection as part of a self-similar system of such events. This turns out to impede the reconnection. As the result LV99 concludes that (4) is not only an upper limit, but is the best estimate of the speed of reconnection.

We stress that the enhanced reconnection efficiency in turbulent fluids is only present if 3D reconnection is considered. In this case Ohmic diffusivity fails to constrain the reconnection process as many field lines simultaneously enter the reconnection region. The number of lines that can do this increases with the decrease of resistivity and this increase overcomes the slow rates of reconnection of individual field lines. It is impossible to achieve a similar enhancement in 2D (see Zweibel 1998) since field lines cannot cross each other.

It worth mentioning that in a recent paper Kim & Diamond (2001) addressed the problem of stochastic reconnection by calculating the turbulent diffusion rate for magnetic flux inside a current sheet. They obtained similar turbulent diffusion rates for both two dimensional and reduced three dimensional MHD. In both cases the presence of turbulence had a negligible effect on the flux transport. The authors pointed out that this would prevent the anomalous transport of magnetic flux within the current sheet and concluded that both 2D and 3D stochastic reconnection proceed at the Sweet-Parker rate even if individual small scale reconnection events happen quickly.

However turbulent diffusion rates within the current sheet are irrelevant for the process of stochastic reconnection (see discussion in Lazarian, Vishniac & Cho 2004, henceforth LVC04). The basic claim in LV99 is that realistic magnetic field topologies allow multiple connections between the current sheet and the exterior environment, which would persist even if the stochastic magnetic field lines were stationary (“frozen in time”) before reconnection. This leads to global outflow constraints which are weak and do not depend on the properties of the current sheet. In particular, the analysis in LV99
assumed that the current sheet thickness is determined purely by ohmic dissipation and that turbulent diffusion of the magnetic field is negligible inside, and outside, the current sheet.

**DOES PARTIAL IONIZATION MATTER?**

The notion that the reconnection may be different in fully ionized and partially ionized gas is not new (see Parker 1977). Reconnection in partially ionized gases has been addressed by various authors (see Naidu, McKenzie & Axford 1992, Zweibel & Brandenburg 1997). In a more recent study Vishniac & Lazarian (1999) considered the diffusion of neutrals away from the reconnection zone assuming anti-parallel magnetic field lines (see also Heitsch & Zweibel 2003a). The ambipolar reconnection rates obtained by Vishniac & Lazarian (1999a), although large compared with the Sweet-Parker model, are insufficient either for fast dynamo models or for the ejection of magnetic flux prior to star formation. In fact, the increase in the reconnection speed stemmed entirely from the compression of ions in the current sheet, with the consequent enhancement of both recombination and ohmic dissipation. This effect is small unless the reconnecting magnetic field lines are almost exactly anti-parallel (Vishniac & Lazarian 1999a, LV99, Heitsch & Zweibel 2003b). Any dynamically significant shared field component will prevent noticeable plasma compression in the current sheet, and lead to speeds practically indistinguishable from the standard Sweet-Parker result. Since generic reconnection regions will have a shared field component of the same order as the reversing component, ambipolar diffusion does not change reconnection speed estimates significantly.

What is the effect of neutrals on stochastic reconnection? It is obvious that neutrals should modify the turbulent cascade at sufficiently small scales. Indeed, while ions move with magnetic fields, neutrals in partially ionized plasma are moved via collisions with ions. The incomplete coupling of ions and neutrals creates friction that damps MHD turbulence. According to LVC04 this gives rise to an interesting new regime of turbulence that creates magnetic stochasticity at scales much smaller than the scale at which neutrals damp turbulent kinetic energy cascade. Eventually, according to LVC04, at very small scales ions decouple from neutrals completely and produce bursts of intermittent in space and time MHD turbulence that involves only ions⁵. While the latter conclusion is still requires testing with two fluid code, the other conclusions of the model, e.g. the formation of magnetic fluctuations at scales smaller than the scale of viscous damping, the spectra of magnetic field and kinetic energy at small scales, the intermittency of magnetic fluctuations, have been successfully tested numerically (Cho, Lazarian & Vishniac 2002, 2003b). With this encouragement from numerics LVC04 applied the expected scaling of magnetic fluctuations to the LV99 stochastic reconnection model and obtained the reconnection rates that depend not only on the intensity of MHD turbulence, but also on the parameters of the partially ionized gas, e.g. on ionization ratio, ion-neutral collision time. Although more restrictive than those

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⁵ This can explain observations by Spangler (1991, 1999) that fail to detect the existence of cut-off of magnetic perturbations in a partially ionized interstellar gas.
given by eq (4) the rates calculated for different idealized phases of interstellar medium, namely, for Warm Ionized Medium, Warm Neutral Medium, Cold Neutral Medium, Molecular Cloud and Dark Cloud are fast enough to enable rapid changes of magnetic field topology.

**HOW CAN TURBULENT RECONNECTION ACCOUNT FOR SOLAR FLARES?**

Solar observations indicate that reconnection can be both slow and fast. Solar flares, which are generally believed to be powered by magnetic reconnection, can happen if oppositely directed magnetic flux can be accumulated for a while without being reconnected. The dynamics of solar flaring seem to show that reconnection events start from some limited volume and spread as though a chain reaction from the initial reconnection region induced a dramatic change in the magnetic field properties. Indeed, solar flaring happens as if the resistivity of plasma were increasing dramatically as plasma turbulence grows (see Dere 1996 and references therein). According to LV99 this is a consequence of the increased stochasticity of the field lines rather than any change in the local resistivity.

If we start with nearly laminar magnetic fields the flaring of reconnection is a natural consequence. Indeed, when turbulence is negligible, i.e. $v_l \to 0$, the field line wandering is limited to the Sweet-Parker current sheet and the Sweet-Parker reconnection scheme takes over. However, the release of energy due to reconnection is likely to induce turbulence in astrophysical fluids. If this is the case, the level of turbulence grows and the turbulent reconnection takes over (LV99). In fact, one may say that reconnection instability takes place as the higher the rate of energy release due to reconnection, the faster reconnection is, which in its turn increases the rate of energy release. It is possible to show that this positive feedback induces finite time instability (Vishniac & Lazarian 1999b), which agrees well with the observations of Solar flares.

**HOW CAN TURBULENT RECONNECTION ACCELERATE COSMIC RAYS?**

There are several ways how magnetic reconnection can accelerate cosmic rays. It is well known that electric fields in the current sheet can do the job. For Sweet-Parker reconnection this may be an important process in those exceptional instances when Sweet-Parker reconnection is fast in astrophysical settings. For Petscheck reconnection only an insubstantial part of magnetic energy is being released within the reconnection zone, while bulk of the energy is being released in shocks that support X-point. Therefore one would expect the shock acceleration of cosmic rays to accompany Petscheck reconnection.

Similarly to the Petscheck scheme the turbulent reconnection process assumes that only small segments of magnetic field lines enter the reconnection zone and are subjected to Ohmic annihilation. Thus only small fraction of magnetic energy, proportional to $R_L^{-2/5}$ (LV99), is released in the current sheets. The rest of the energy is released in the
FIGURE 2. Cosmic rays spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move towards each other with the reconnection velocity $V_R$. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of $V_A$. Bouncing at points A and B happens because either of streaming instability or turbulence in the reconnection region.

form of non-linear Alfvén waves that are generated as reconnected magnetic field lines straighten up. Such waves are likely to cause second order Fermi acceleration. This idea was briefly discussed in Lazarian et al. (2001) in relation to particle acceleration during the gamma-ray burst events. In addition, large amplitude Alfvénic motions in low $\beta$, i.e. magnetically dominated, plasmas are likely to induce shocks (see Beresnyak, Lazarian & Cho 2005), which can also cause particle acceleration.

However, the most interesting process is the first-order Fermi acceleration that is intrinsic to the turbulent reconnection. To understand it consider a particle entrained on a reconnected magnetic field line (see Fig. 2). This particle may bounce back and force between magnetic mirrors formed by oppositely directed magnetic fluxes moving towards each other with the velocity $V_R$. Each of such bouncing will increase the energy of a particle in a way consistent with the requirements of the first-order Fermi process. The interesting property of this mechanism that potentially can be used to test observationally the idea is that the resulting spectrum is different from those arising from shocks. Gouveia Dal Pino & Lazarian (2003) used particle acceleration within turbulent reconnection regions to explain the synchrotron power-law spectrum arising from the flares of the microquasar GRS 1915+105. Note, that the mechanism acts in the Sweet-Parker scheme as well as in the scheme of turbulent reconnection. However, in the former the rates of reconnection and therefore the efficiency of acceleration are marginal in most cases.

As a note of caution we would like to warn our reader that the detailed theory of cosmic ray acceleration during turbulent reconnection that accounts for both first and
second order Fermi acceleration is yet to be developed\(^6\) However, this seems to be an interesting way for approaching the cosmic ray acceleration problem.

### WHAT ARE OTHER IMPLICATIONS?

#### Star formation

It is well known that the frozenness of magnetic field condition should be violated during star formation. Otherwise, stars would have magnetic fields orders of magnitude larger than the observed values. Magnetic field removal is also an important ingredient of the evolution of star-forming magnetized clouds. While usually these issues are addressed through appealing to ambipolar diffusion (see Tassis & Mouschovias 2005), turbulent reconnection in partially ionized gas described in LVC04 is well suited for doing the job. Note, that ambipolar diffusion is too slow at least for supercritical star formation that takes place over free fall time. This problem does not arise for turbulent reconnection. While the very idea that reconnection can be an important component of star formation was advocated for a while by Frank Shu, the quantitative implementation of it was impeded by the absence of reliable estimates of the reconnection rate.

#### Transport processes

Various astrophysical transport processes are affected by reconnection. Let us start with the process of heat transport. Cho et al. (2003) has shown numerically that heat can be efficiently transported by turbulent eddies within magnetized fluid thus preventing cooling flows from forming in clusters of galaxies. Such a mixing is difficult to visualize unless magnetic fields change their topology rather than form magnetic knots (Lazarian & Cho 2004). Similarly transport of matter is affected by reconnection. Without it cosmic rays, ions, charged dust particles would always be frozen in on “their own” magnetic field lines, which would drastically impede mixing processes on astrophysical scales. In addition, transport of angular momentum in accretion disks is expected to be very different depending on the rate of reconnection. Fast turbulent reconnection should prevent direct magnetic connection of elements that are at very different radial distances from the center. This does limit the efficiency of the angular momentum transport.

#### Dynamo

Mean field dynamo is an elegant theory explaining the origin of astrophysical magnetic fields via amplification of the seed field by fluid motions (see Moffatt 1978, Parker 1979). The original seed field may be tiny and in some sense its value is frequently irrelevant provided that an efficient dynamo has enough time to operate. Fast reconnection is a necessary part the theory. Problems and approaches to mean field dynamo are discussed in a recent review by Vishniac, Lazarian & Cho (2003). It worth noting that the stochastic reconnection dissipates only insignificant part of the magnetic energy through Ohmic

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\(^6\) The following points that must be taken into account while calculating cosmic ray acceleration. First of all, the streaming instability is partially suppressed due to a non-linear interaction with ambient MHD turbulence (Yan & Lazarian 2002, 2004, Farmer & Goldreich 2004). For cosmic ray scattering from turbulent fluctuations it is absolutely essential that the proper scaling of MHD modes is taken (Chandran 2000, Yan & Lazarian 2002).
heating and therefore it does not remove the constraint given by the helicity conservation. A mean field dynamo model proposed by Vishniae & Cho (2002) takes explicitly this constraint into account.

Other implications, e.g. self-consistency of strong Alfvénic turbulence, heating of electrons in accretion flows, and heating of interestellar gas are discussed in LV99 and Lazarian & Vishniac (2000).

HOW TO TEST IDEAS ABOVE?

It has been shown in the paper above that turbulent reconnection affects many essential astrophysical processes. Therefore it is important to test the model.

Implications of turbulent reconnection provide an indirect way to test the model. Thus a way of testing the model is through making quantitative predictions of the reconnection effects that can be tested. Solar flares, spectra of particles emerging during reconnection are examples of such effects. A search for signatures of Petscheck reconnection, e.g. for the large scale X-points that should be observable, provides another indirect way of searching for the truth.

Turbulent reconnection can be tested directly in laboratory. The problem there is that the microscale and macroscale are usually not so far apart for laboratory experiments. To distinguish between plasma turbulence effects and MHD effects that our model deals with, the amplitudes of magnetic perturbations should be substantial.

Numerical testing of turbulent reconnection looks at the moment as the most promising way to go. With computers getting more powerful it is feasible to test the predictions obtained in LV99. Testing reconnection rates in partially ionized gas (LVC04) looks very challenging, but doable in future using two fluid codes.

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