RevMexAA (Serie de Conferencias), **9**, 55–62 (2000)

FAST RECONNECTION OF MAGNETIC FIELDS IN TURBULENT FLUIDS

A. Lazarian

Department of Astronomy, University of Wisconsin-Madison, USA

and

E. Vishniac

Department of Physics and Astronomy, Johns Hopkins University, Baltimore, USA

RESUMEN

La reconección es el proceso mediante el cual los campos magnéticos cambian de topología en un medio conductor, y es fundamental para entender diferentes procesos, incluyendo la turbulencia interestelar y los dinamos estelares y galácticos. Para explicar el campo galáctico, las ráfagas y el ciclo solar, la reconección debe ser rápida y propagarse a la velocidad de Alfvén. Trabajos anteriores consideraban fluidos laminares y obtenían tasas de reconección pequeñas. Mostramos que la presencia de una componente aleatoria del campo magnético permite una *reconnección rápida* ya que, a diferencia del caso laminar donde el proceso avanza línea por línea, en el caso turbulento participan muchas líneas simultáneamente. Una fracción importante de la energía magnética se va a la turbulencia MHD, lo cual aumenta la tasa de reconección al aumentar la parte aleatoria del campo. Como consecuencia, los dinamos solares y galácticos también se vuelven rápidos.

ABSTRACT

Reconnection is the process by which magnetic fields in a conducting fluid change their topology. This process is essential for understanding a wide variety of astrophysical processes, including stellar and galactic dynamos and astrophysical turbulence. To account for solar flares, solar cycles, and the structure of the galactic magnetic field, reconnection must be fast, propagating with a speed close to the Alfvén speed. Earlier attempts to deal with magnetic reconnection assumed that magnetized fluids are laminar and as a result obtained slow reconnection rates. We show that the presence of a random magnetic field component substantially enhances the reconnection rate and enables *fast reconnection*, i.e., reconnection that does not depend on fluid resistivity. The enhancement of the reconnection rate is achieved via a combination of two effects. First of all, only small segments of magnetic field lines are subject to direct Ohmic annihilation. Thus the fraction of magnetic energy that goes directly into fluid heating goes to zero as fluid resistivity vanishes. However, the most important enhancement comes from the fact that unlike the laminar fluid case where reconnection is constrained to proceed line by line, the presence of turbulence enables many magnetic field lines to enter the reconnection zone simultaneously. A significant fraction of magnetic energy goes into MHD turbulence and this enhances reconnection rates through an increase in the field stochasticity. In this way magnetic reconnection becomes fast when field stochasticity is accounted for. As a consequence solar and galactic dynamos are also fast, i.e., do not depend on fluid resistivity.

Key Words: **GALAXIES: MAGNETIC FIELDS — ISM: MAGNETIC FIELDS —MAGNETIC FIELDS — MHD — SUN: MAGNETIC FIELDS**

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

1. FLUX FREEZING AND RECONNECTION

Plasma conductivity is high for most astrophysical circumstances. This suggests that "flux freezing", where magnetic field lines move with the local fluid elements, is usually a good approximation within astrophysical magnetohydrodynamics (MHD). The coefficient of magnetic field diffusivity in a fully ionized plasma is $\eta = c^2/(4\pi\sigma) = 10^{13}T^{3/2}$ s^{-1} cm^2 s^{-1}, where $\sigma = 10^7 T^{3/2}$ s^{-1} is the plasma conductivity and T is the electron temperature. The characteristic time for field diffusion through a plasma slab of size y is y^2/η, which is large for any "astrophysical" y.

What happens when magnetic field lines intersect? Do they deform each other and bounce back or they do change their topology? This is the central question of the theory of magnetic reconnection. In fact, the whole dynamics of magnetized fluids and the back-reaction of the magnetic field depends on the answer.

Magnetic reconnection is a long standing problem in theoretical MHD. This problem is closely related to the hotly debated issue of the magnetic dynamo (see Parker 1979; Moffatt 1978; Krause & Radler 1980). Indeed, it is impossible to understand the amplification of large scale magnetic fields without a knowledge of the mobility and reconnection of magnetic fields. Dynamo action invokes a constantly changing magnetic field topology[1] and this requires efficient reconnection despite very slow Ohmic diffusion rates.

2. THE SWEET-PARKER SCHEME AND ITS MODIFICATIONS

The literature on magnetic reconnection is rich and vast (see e.g., Biskamp 1993 and references therein). We start by discussing a robust scheme proposed by Sweet and Parker (Parker 1957; Sweet 1958). In this scheme oppositely directed magnetic fields are brought into contact over a region of L_x size (see Fig. 1). The diffusion of magnetic field takes place over the vertical scale Δ which is related to the Ohmic diffusivity by $\eta \approx V_r\Delta$, where V_r is the velocity at which magnetic field lines can get into contact with each other and reconnect. Given some fixed η one may naively hope to obtain fast reconnection by decreasing Δ. However, this is not possible. An additional constraint posed by mass conservation must be satisfied. The plasma initially entrained on the magnetic field lines must be removed from the reconnection zone. In the Sweet-Parker scheme this means a bulk outflow through a layer with a thickness of Δ. In other words, the entrained mass must be ejected, i.e., $\rho V_r L_x = \rho' V_A \Delta$, where it is assumed that the outflow occurs at the Alfvén velocity. Ignoring the effects of compressibility, then $\rho = \rho'$ and the resulting reconnection velocity allowed by Ohmic diffusivity and the mass constraint is $V_r \approx V_A \mathcal{R}_L^{-1/2}$, where $\mathcal{R}_L^{-1/2} = (\eta/V_A L_x)^{1/2}$ is the Lundquist number. This is a very large number in astrophysical contexts (as large as 10^{20} for the Galaxy) so that the Sweet-Parker reconnection rate is negligible.

It is well known that using the Sweet-Parker reconnection rate it is impossible to explain solar flares and it is impossible to reconcile dynamo predictions with observations. Are there any ways to increase the reconnection rate? In general, we can divide schemes for fast reconnection into those which alter the microscopic resistivity, broadening the current sheet, and those which change the global geometry, thereby reducing L_x. An example of the latter is the suggestion by Petschek (1964) that reconnecting magnetic fields would tend to form structures whose typical size in all directions is determined by the resistivity ('X-point' reconnection). This results in a reconnection speed of order $V_A/\ln \mathcal{R}_L$. However, attempts to produce such structures in simulations of reconnection have been disappointing (Biskamp 1984, 1986). In numerical simulations the X-point region tends to collapse towards the Sweet-Parker geometry as the Lundquist number becomes large (Biskamp 1996; Wang, Ma, & Bhattacharjee 1996). One way to understand this collapse is to consider perturbations of the original X-point geometry. In order to maintain this geometry reconnection has to be fast, which requires shocks in the original (Petschek) version of this model. These shocks are, in turn, supported by the flows driven by fast reconnection, and fade if L_x increases. Naturally, the dynamical range for which the existence of such shocks is possible depends on the Lundquist number and shrinks when fluid conductivity increases. The apparent conclusion is that at least in the collisional regime reconnection occurs through narrow current sheets.

In the collisionless regime the width of the current sheets may be determined by the ion cyclotron (or Larmor) radius r_c (Parker 1979) or by the ion skin depth (Ma & Bhattacharjee 1996; Biskamp, Schwarz, & Drake 1997; Shay et al. 1998) which differs from the former by the ratio of V_A to ion thermal velocity.

[1] Merely winding up a magnetic field can increase the magnetic field energy, but cannot increase the magnetic field flux. We understand dynamos in the latter sense. The Zel'dovich "fast" dynamo (Vainshtein & Zel'dovich 1972) also invokes reconnection for continuous dynamo action (Vainshtein 1970).

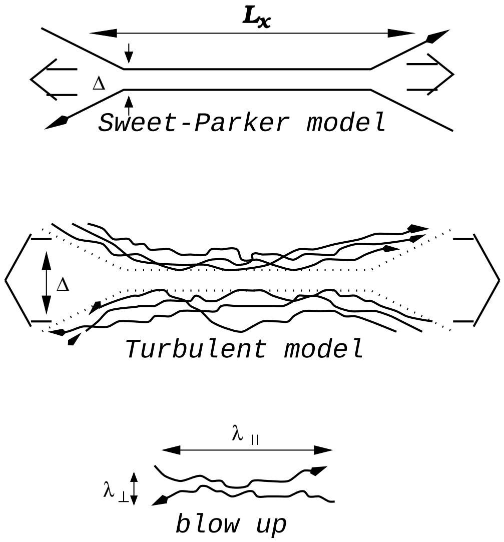

Fig. 1. (*Top*) Sweet-Parker scheme of reconnection. (*Middle*) The new scheme of reconnection that accounts for field stochasticity. (*Bottom*) A blow up of the contact region. Thick arrows depict outflows of plasma.

In laboratory conditions this often leads to a current sheet thickness which is much larger than expected ('anomalous resistivity'). However, this effect is not likely to be important in the interstellar medium. The thickness of the current sheet Δ scales in the Sweet-Parker scheme as $L_x^{1/2}$. Therefore, for a sufficiently large L_x the natural Sweet-Parker sheet thickness becomes larger than the thickness entailed by anomalous effects. Note that the ion Larmor radius r_c in an interstellar magnetic field is about a hundred kilometers. One cannot really hope to squeeze quickly the matter from many parsecs through a slot of this size!

One may invoke anomalous resistivity to stabilize the X-point reconnection for collisionless plasma. For instance, Shay et al. (1998) found that the reconnection speed in their simulations was independent of L_x, which would suggest that something like Petschek reconnection emerges in the collisionless regime. However, their dynamic range was small and the ion ejection velocity increased with L_x, with maximum speeds approaching V_A for their largest values of L_x. Assuming that V_A is an upper limit on ion ejection speeds we may expect a qualitative change in the scaling behavior of their simulations at slightly larger values of L_x. One may expect the generic problems intrinsic to X-point reconnection to persist for large $\mathcal{R}_L$.

If neither anomalous resistivity or/and X-point reconnection work, are there any other ways to account for fast reconnection? Can reconnection speeds be substantially enhanced if the plasma coupling with magnetic field is imperfect? This is the case in the presence of Bohm diffusion, which is a process that is observed in laboratory plasma but lacks a good theoretical explanation. Its characteristic feature is that ions appear to scatter about once per Larmor precession period. The resulting particle diffusion destroys the 'frozen-in' condition and allows significant larger magnetic field line diffusion. The effective diffusivity of magnetic field lines is $\eta_{\rm Bohm} \sim V_A r_c$ (see Lazarian & Vishniac 1999, henceforth LV99) which is a large increase over Ohmic resistivity. The major shortcoming of this idea is that it is unclear at all whether the concept of Bohm diffusion is applicable to astrophysical circumstances. Moreover, we note that even if we make this substitution, it can produce fast reconnection, of order V_A, only if $r_c \sim L_x$. It therefore fails as an explanation for fast reconnection for the same reason that anomalous resistivity does.

Matter may also diffuse perpendicular to magnetic field lines if the plasma is partially ionized. Since neutrals are not directly affected by magnetic field lines the neutral outflow layer may be much broader than the Δ determined by Ohmic diffusivity. The trouble with ambipolar diffusion is that ions and electrons are left in the reconnection zone. As a result, the reconnection speed is determined by a slow recombination process. Calculations in Vishniac & Lazarian (1999) show that the ambipolar reconnection rates are slow unless the ionization ratio is extremely low.

Can plasma instabilities increase the reconnection rate? The narrow current sheet formed during Sweet-Parker reconnection is unstable to tearing modes. A study of tearing modes in LV99 showed that an increase over the Sweet-Parker rates is possible and the resulting reconnection rates may be as high as $V_A \mathcal{R}_L^{3/10}$. However, these speeds are still exceedingly small in view of the enormous values of $\mathcal{R}_L$ encountered in astrophysical plasmas. Below we discuss a different approach to the problem of rapid reconnection i.e., we consider magnetic

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

reconnection[2] in the presence of a weak random field component.

3. TURBULENT RECONNECTION

3.1. *Reconnection in Two and Three Dimensions*

Two idealizations were used in the preceding discussion. First, we considered the process in only two dimensions. Second, we assumed that the magnetized plasma is laminar. The Sweet-Parker scheme can easily be extended into three dimensions. Indeed, one can always take a cross-section of the reconnection region such that the shared component of the two magnetic fields is perpendicular to the cross-section. In terms of the mathematics nothing changes, but the outflow velocity becomes a fraction of the total V_A and the shared component of the magnetic field will have to be ejected together with the plasma. This result has motivated researchers to do most of their calculations in 2D, which has obvious advantages for both analytical and numerical investigations.

However, physics in two and three dimensions is very different. For instance, in two dimensions the properties of turbulence are very different. In LV99 we considered three dimensional reconnection in a turbulent magnetized fluid and showed that reconnection is fast. This result cannot be obtained by considering two dimensional turbulent reconnection (cf. Matthaeus & Lamkin 1986). Below we briefly discuss the idea of turbulent reconnection, while the full treatment of the problem is given in LV99.

3.2. *A Model of Turbulent Reconnection*

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, 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. This field may, or may not, be ordered on the largest conceivable scales. However, we will consider scales smaller than the typical radius of curvature of the magnetic field lines, or alternatively, scales below the peak in the power spectrum of the magnetic field, so that the direction of the unperturbed magnetic field is a reasonably well defined concept. 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 $\lambda_\|$ with a correlation distance $\lambda_\perp$ across field lines (see Fig. 1).

The modification of the mass conservation constraint 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; the progress of reconnection in the current sheet itself 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 $\lambda_\| \ll L_x$ (see Fig. 1), which is the scale over which a magnetic field line deviates from its original direction by the thickness of the Ohmic diffusion layer $\lambda_\perp^{-1} \approx \eta/V_{rec,local}$. If the angle ϕ 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 ϕ does depend on scale. Therefore, the *local* reconnection rate $V_{rec,local}$ is given by the usual Sweet-Parker formula but with $\lambda_\|$ instead of L_x, i.e., $V_{rec,local} \approx V_A(V_A\lambda_\|/\eta)^{-1/2}$. It is obvious from Figure 1 that $\sim L_x/\lambda_\|$ magnetic field lines will undergo reconnection simultaneously (compared to a one by one line reconnection process for the Sweet-Parker scheme). Thus, the overall reconnection rate may be as large as $V_{rec,global} \approx V_A(L_x/\lambda_\|)(V_A\lambda_\|/\eta)^{-1/2}$. Whether or not this limit is important depends on the value of $\lambda_\|$.

[2]The mode of reconnection discussed here is sometimes is called *free* reconnection as opposed to *forced* reconnection. Wang et al. (1992) define *free* reconnection as a process caused by a nonideal instability driven by the free energy stored in an equilibrium. If the equilibrium is stable, reconnection can be forced if a perturbation is applied externally.

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

The relevant values of $\lambda_{\|}$ and $\langle y^2 \rangle^{1/2}$ depend on the magnetic field statistics. This calculation was performed in LV99 using the Goldreich-Sridhar (1995) model of MHD turbulence, the Kraichnan model (Iroshnikov 1963; Kraichnan 1965) and for MHD turbulence with an arbitrary spectrum. In all the cases the upper limit on $V_{rec,global}$ was greater than V_A, so that the diffusive wandering of field lines imposed the relevant limit on reconnection speeds. For instance, for the Goldreich-Sridhar (1995) spectrum the upper limit on the reconnection speed was

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

where l and v_l are the energy injection scale and turbulent velocity at this scale, respectively. In LV99 we also considered other processes that can impede reconnection and find that they are 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 limit reconnection to speeds less than V_A, which is obviously true regardless. As a result, we showed in LV99 that equation (1) is not only an upper limit, but is the best estimate of the speed of reconnection.

Naturally, 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, in practical terms this means an artificially low level of turbulence that should not be expected in realistic astrophysical environments. Moreover, the release of energy due to reconnection, at any speed, will contribute to the turbulent cascade of energy and help drive the reconnection speed upward.

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 can not cross each other.

3.3. *Energy Dissipation and its Consequences*

It is usually believed that rapid reconnection in the limit of vanishing resistivity implies a current singularity (Park, Monticello, & White 1984). Our model does not require such singularities. Indeed, they show that while the amount of Ohmic dissipation tends to 0 as $\eta \to 0$, the smallest scale of the magnetic field's stochastic component decreases so that the rate of the flux reconnection does not decrease.

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 a small fraction of the magnetic energy, proportional to $\mathcal{R}_L^{-2/5}$ (LV99), is released in the form of ohmic heat. The rest of the energy is released in the form of non-linear Alfvén waves that are generated as reconnected magnetic field lines straighten up.

Naturally, the low efficiency of electron heating is of little interest when ion and electron temperatures are tightly coupled. When this is not the case the LV99 model for reconnection has some interesting consequences. As an example, we may consider advective accretion flows (ADAFs), following the general description given in Narayan & Yi (1995) in which advective flows can be geometrically thick and optically thin with a small fraction of the dissipation going into electron heating. If, as expected, the magnetic pressure is comparable to the gas pressure in these systems, then a large fraction of the orbital energy dissipation occurs through reconnection events. If a large fraction of this energy goes into electron heating (cf. Bisnovatyi-Kogan & Lovelace 1997) then the observational arguments in favor of ADAFs are largely invalidated. The results in LV99 suggest that reconnection, by itself, will not result in channeling more than a small fraction of the energy into electron heating. Of course, the fate of energy dumped into a turbulent cascade in a collisionless magnetized plasma then becomes a critical issue.

We also note that observations 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 initiated 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). In our picture this is a consequence of the increased stochasticity of the field lines rather than any change in the local resistivity.

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

The change in magnetic field topology that follows localized reconnection provides the energy necessary to feed a turbulent cascade in neighboring regions. This kind of nonlinear feedback is also seen in the geomagnetic tail, where it has prompted the suggestion that reconnection is mediated by some kind of nonlinear instability built around modes with very small $k_{\|}$ (cf. Chang 1998 and references therein). The most detailed exploration of nonlinear feedback can be found in the work of Matthaeus & Lamkin (1986), who showed that instabilities in narrow current sheets can sustain broadband turbulence in two dimensional simulations. Although our model is quite different, and relies on the three dimensional wandering of field lines to sustain fast reconnection, we note that the concept of a self-excited disturbance does carry over and may describe the evolution of reconnection between volumes with initially smooth magnetic fields.

4. IMPLICATIONS

4.1. *Turbulent Reconnection and Turbulent Diffusivity*

We would like to stress that in introducing turbulent reconnection we do not intend to revive the concept of "turbulent diffusivity" as used in dynamo theories (Parker 1979). In order to explain why astrophysical magnetic fields do not reverse on very small scales, researchers have usually appealed to an *ad hoc* diffusivity which is many orders of magnitude greater than the ohmic diffusivity. This diffusivity is assumed to be roughly equal to the local turbulent diffusion coefficient. While superficially reasonable, this choice implies that a dynamically significant magnetic field diffuses through a highly conducting plasma in much the same way as a passive tracer. This is referred to as turbulent diffusivity and denoted η_t, as opposed to the Ohmic diffusivity η. Its name suggests that turbulent motions subject the field to kinematic swirling and mixing. As the field becomes intermittent and intermixed it can be assumed to undergo dissipation at arbitrarily high speeds.

Parker (1992) showed convincingly that the concept of turbulent diffusion is ill-founded. He pointed out that turbulent motions are strongly constrained by magnetic tension and large scale magnetic fields prevent hydrodynamic motions from mixing magnetic field regions of opposing polarity unless they are precisely anti-parallel. However, results in LV99 show that the mobility of a magnetic field in a turbulent fluid is indeed enhanced. For instance, due to fast reconnection the magnetic field will not form long lasting knots. Moreover, the magnetic field can be expected to straighten itself and remove small scale reversals as required, in a qualitative sense, by dynamo theory. Nevertheless, the underlying physics of this process is very different from what is usually meant by "turbulent diffusivity". Within the turbulent diffusivity paradigm, magnetic fields of different polarity were believed to filament and intermix on very small scales while reconnection proceeded slowly. On the contrary, we have shown in LV99 that the global speed of reconnection is fast if a moderate degree of magnetic field line wandering is allowed. The latter, unlike the former, corresponds to a realistic picture of MHD turbulence and does not entail prohibitively high magnetic field energies at small scales.

On the other hand, the diffusion of particles through a magnetized plasma is greatly enhanced when the field is mildly stochastic. There is an analogy between the reconnection problem and the diffusion of cosmic rays (Barghouty & Jokipii 1996). In both cases charged particles follow magnetic field lines and in both cases the wandering of the magnetic field lines leads to efficient diffusion.

4.2. *Dynamos*

There is a general belief that magnetic dynamos operate in stars, galaxies (Parker 1979) and accretion disks (Balbus & Hawley 1998). In stars, and in many accretion disks, the plasma has a high β, that is the average plasma pressure is higher than the average magnetic pressure. In such situations the high diffusivity of the magnetic field can be explained by concentrating flux in tubes[3] (Vishniac 1995a,b). This trick does not work in the disks of galaxies, where the magnetic field is mostly diffuse (compare Subramanian 1998) and ambipolar diffusion impedes the formation of flux tubes (Lazarian & Vishniac 1996). This is the situation where our current treatment of magnetic reconnection is most relevant. However, our results suggest that magnetic reconnection proceeds regardless and that the concentration of magnetic flux in flux tubes via turbulent pumping is not a necessary requirement for successful dynamos in stars and accretion discs.

[3]Note that flux tube formation requires initially high reconnection rates. Therefore, the flux tubes by themselves provide only a partial solution to the problem.

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

To enable sustainable dynamo action and, for example, generate a galactic magnetic field, it is necessary to reconnect and rearrange magnetic flux on a scale similar to a galactic disc thickness within roughly a galactic turnover time ($\sim 10^8$ years). This implies that reconnection must occur at a substantial fraction of the Alfvén velocity. The preceding arguments indicate that such reconnection velocities should be attainable if we allow for a realistic magnetic field structure, one that includes both random and regular fields.

One of the arguments against traditional mean-field dynamo theory is that the rapid generation of small scale magnetic fields suppresses further dynamo action (e.g., Kulsrud & Anderson 1992). Our results thus far show that a random magnetic field enhances reconnection by enabling more efficient diffusion of matter from the reconnection layer. This suggests that the existence of small scale magnetic turbulence is a prerequisite for a successful large scale dynamo. In other words, we are arguing for the existence of a kind of negative feed-back. If the magnetic field is too smooth, reconnection speeds decrease and the field becomes more tangled. If the field is extremely chaotic, reconnection speeds increase, making the field smoother. We note that it is common knowledge that magnetic reconnection can sometimes be quick and sometimes be slow. For instance, the existence of bundles of flux tubes of opposite polarity in the solar convection zone indicates that reconnection can be very slow. At the same time, solar flaring suggests very rapid reconnection rates.

Our results show that in the presence of MHD turbulence magnetic reconnection is fast, and this in turn allows the possibility of 'fast' dynamos in astrophysics (see the discussion of the *fast dynamo* in Parker 1992).

Finally, we have assumed that we are dealing with a strong magnetic field, where motions that tend to mix field lines of different orientations are largely suppressed. The galactic magnetic field is usually taken to have grown via dynamo action from some extremely weak seed field (cf. Zel'dovich, Ruzmaikin, & Sokoloff 1983; Lazarian 1992 and references contained therein). When the field is weak it can be moved as a passive scalar and its spectrum will mimic that of Kolmogorov turbulence. The difference between $\lambda_{\perp}$ and $\lambda_{\|}$ vanishes, the field becomes tangled on small scales, and $V_{rec,local}$ becomes of the order of V_A. Of course, in this stage of evolution V_A may be very small. However, on such small scales V_A will grow to equipartition with the turbulent velocities on the turn over time of the small eddies. The enhancement of reconnection as V_A increases accelerates the inverse cascade as small magnetic loops merge to form larger ones.

5. DISCUSSION

It is not possible to understand the dynamics of magnetized astrophysical plasmas without understanding how magnetic fields reconnect. Here we have compared traditional approaches to the problem of magnetic reconnection and a new approach that includes the presence of turbulence in the magnetized plasma.

One of the more striking aspects of our result is that the global reconnection speed is relatively insensitive to the actual physics of reconnection. Equation (1) only depends on the nature of the turbulent cascade. Although this conclusion was reached by invoking a particular model for the strong turbulent cascade, we showed in LV99 that any sensible model gives qualitatively similar results. One may say that the conclusion that reconnection is fast, even when the local reconnection speed is slow, represents a triumph of global geometry over the slow pace of ohmic diffusion. In the end, reconnection can be fast because if we consider any particular flux element inside the contact volume, assumed to be of order L_x^3, the fraction of the flux element that actually undergoes microscopic reconnection vanishes as the resistivity goes to zero.

The new model of fast turbulent reconnection changes our understanding of many astrophysical processes. Firstly, it explains why dynamos do not suppress themselves through the excessive generation of magnetic noise, as some authors suggest (Kulsrud & Anderson 1992). The model also explains why reconnection may be sometimes fast and sometimes slow, as solar activity demonstrates. ADAFs and the acceleration of cosmic rays at reconnection sites are other examples of processes where a new model of reconnection should be applied.

Our results on turbulent reconnection assume that the turbulent cascade is limited by plasma resistivity. If gas is partially ionized collisions with neutrals may play an important role in damping turbulence. A study in Lazarian & Vishniac (2000) shows that for gas with low levels of ionization turbulent reconnection may be impeded as magnetic field wandering is suppressed on small scales. However, the level of suppression depends on the details of the energy injection into the turbulent cascade (see a discussion in Lazarian & Pogosyan 2000), which are far from being clear. Moreover, for very low ionization levels there will be an enhancement of the reconnection process as neutrals diffuse perpendicular to magnetic field lines. Thus, reconnection may still be an important process in the evolution of molecular clouds and in star formation.

AL acknowledges valuable discussions with Chris McKee.

REFERENCES

Balbus, S. A., & Hawley, J. F. 1998, Rev. Mod. Phys., 1, 1
Barghouty, A. F., & Jokipii, J. R. 1996, ApJ, 470, 858
Biskamp, D. 1984, Phys. Lett. A, 105, 124
_________. 1986, Phys. Fluids, 29, 1520
_________. 1993, Nonlinear Magnetohydrodynamics, (Cambridge: Cambridge University Press)
_________. 1996, ApSS, 242, 165
Biskamp, D., Schwarz, E., & Drake, J. F. 1997, Phys. Plasmas, 4, 1002
Bisnovatyi-Kogan, G. S., & Lovelace, R. V. E. 1997, ApJ, 486, L43
Chang, T. 1998, in AGU Monographs Vol. 104, Geospace Mass and Energy Flow, ed. J. L. Horwitz, D. L. Gallagher, & W. K. Peterson (Washington DC: American Geophysical Union) p. 193
Dere, K. P. 1996, ApJ, 472, 864
Goldreich, P., & Sridhar, S. 1995, ApJ, 438, 763
Iroshnikov, P. S. 1963, AZh, 40, 742
Kraichnan, R. H. 1965, Phys. Fluids, 8, 1385
Krause, F., & Radler, K. H. 1980, Mean-Field Magnetohydrodynamics and Dynamo Theory (Oxford: Pergamon)
Kulsrud, R. M., & Anderson, S. W. 1992, ApJ, 396, 606
Lazarian, A. 1992, A&A, 264, 326
Lazarian, A., & Pogosyan, D. 2000, ApJ, in press
Lazarian, A., & Vishniac, E. T. 1996, in ASP Conf. Ser. Vol. 97, Polarimetry of the Interstellar Medium, ed. W. G. Roberge & D. C. B. Whittet (San Francisco: ASP), 537
_________. 1999, ApJ, 517, 700
_________. 2000 ApJ, in preparation
Ma, Z. W., & Bhattacharjee, A. 1996, Geophys. Res. Lett., 23(21), 2955
Matthaeus, W. H., & Lamkin, S. L. 1986, Phys. Fluids, 29(8), 2513
Moffatt, H. K. 1978, Magnetic Field Generation in Electrically Conducting Fluids (Cambridge: Cambridge University Press)
Narayan, R., & Yi, I. 1995, ApJ, 452, 710
Park, W., Monticello, D. A., & White, R. B. 1984, Phys. Fluids, 27, 137
Parker, E. N. 1957, J. Geophys. Res., 62, 509
_________. 1979, Cosmical Magnetic Fields (Oxford: Clarendon Press)
_________. 1992, ApJ, 401, 137
Petschek, H. E. 1964, The Physics of Solar Flares, AAS-NASA Symposium (NASA SP-50), ed. W. H. Hess (Greenbelt, MD: NASA), 425
Shay, M. A., Drake, J. F., Denton, R. E., & Biskamp, D. 1998, J. Geophys. Res., 103, 9165
Sweet, P. A. 1958, in IAU Symp. 6, Electromagnetic Phenomena in Cosmical Plasma, ed. B. Lehnert (New York: Cambridge Univ. Press), 123
Subramanian, K. 1998, MNRAS, 294, 718
Vainshtein, S. I. 1970, Sov. Phys. - JETP Lett., 31, 87
Vainshtein, S. I. & Zel'dovich, Ya. B. 1972, Sov. Phys. - Uspekhi, 15, 159
Vishniac, E. T. 1995a, ApJ, 446, 724
_________. 1995b, ApJ, 451, 816
Vishniac, E. T., & Lazarian, A. 1999, ApJ, 511, 193
Wang, X., Ma, Z. W., & Bhattacharjee, A. 1992, Phys. Fluids B, 4, 1795
_________. 1996, Phys. Plasmas, 3(5), 2129
Zel'dovich, Ya. B., Ruzmaikin, A. A., & Sokoloff, D. D. 1983, Magnetic Fields in Astrophysics (New York: Gordon and Breach)
Zweibel, E. 1998, Phys. Plasmas, 5, 247

A. Lazarian: Dept. of Astronomy, University of Wisconsin, 5534 Sterling Hall, 475 N. Charter St., Madison, WI 53706, USA (lazarian@astro.wisc.edu).
E. Vishniac: Dept. of Physics and Astronomy, Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA (ethan@pha.jhu.edu).

Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco