RevMexAA (Serie de Conferencias), **36**, 81–88 (2009)

MODEL OF RECONNECTION OF WEAKLY STOCHASTIC MAGNETIC FIELD AND ITS IMPLICATIONS

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RESUMEN

Discutimos el modelo de reconección magnética en presencia de turbulencia que introdujimos hace diez años. El modelo no requiere de efectos de plasma para producir reconexión rápida. De hecho, muestra que el nivel de estocasticidad del campo magnético controla la reconexión. El modelo supone turbulencia sub-Alfvénica, con un campo magnético perturbado sólo de forma ligera. Ésto asegura que la reconexión ocurra de forma general en ambientes astrofísicos, y que el modelo no apele a ningún concepto no físico, como a la difusividad magnética turbulenta empleada en el dínamo magnético cinético. El interés en el modelo se ha incrementado recientemente dado al éxito de pruebas numéricas de las predicciones analíticas. En vista a lo anterior, discutimos implicaciones del modelo, que incluyen la aceleración de rayos cósmicos por el proceso de aceleración de Fermi de primer orden inherente al modelo, brotes de reconexión que pueden ser asociados a erupciones solares, así como la disipación de flujo magnético durante la formación estelar.

ABSTRACT

We discuss the model of magnetic field reconnection in the presence of turbulence introduced by us ten years ago. The model does not require any plasma effects to be involved in order to make the reconnection fast. In fact, it shows that the degree of magnetic field stochasticity controls the reconnection. The turbulence in the model is assumed to be sub-Alfvénic, with the magnetic field only slightly perturbed. This ensures that the reconnection happens in generic astrophysical environments and the model does not appeal to any unphysical concepts, similar to the turbulent magnetic diffusivity concept, which is employed in the kinematic magnetic dynamo. The interest to that model has recently increased due to successful numerical testings of the model predictions. In view of this, we discuss implications of the model, including the first-order Fermi acceleration of cosmic rays, that the model naturally entails, bursts of reconnection, that can be associated with Solar flares, as well as, removal of magnetic flux during star-formation.

Key Words: galaxies: magnetic fields — MHD — Sun: energetic particles — Sun: flares — Sun: magnetic fields

1. PROBLEM OF ASTROPHYSICAL RECONNECTION

Plasma conductivity is high in most astrophysical circumstances. This suggests that “flux freezing”, where magnetic field lines move with the local fluid elements, is a good approximation within astrophysical magnetohydrodynamics (MHD).

But, what happens when magnetic field lines intersect? 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.

2. THE SWEET-PARKER MODEL VERSUS PETSCHEK MODEL

The literature on magnetic reconnection is rich and vast (see e.g., Priest & Forbes 2000, 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 Figure 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

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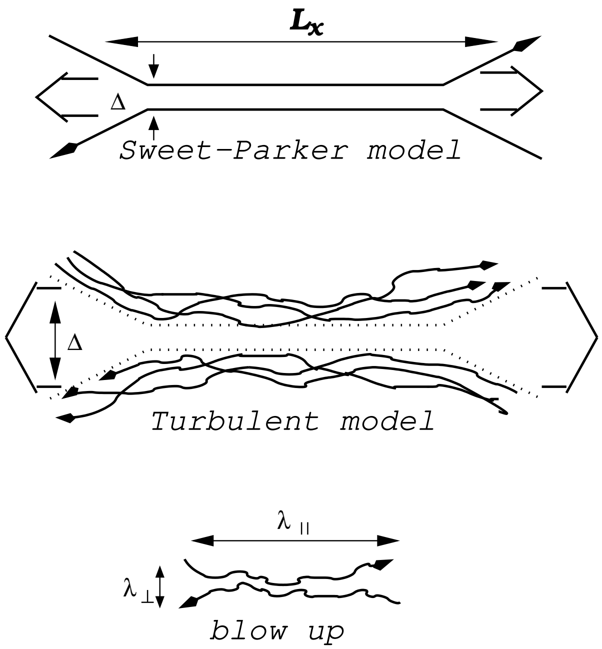

Fig. 1. *Upper panel*: Sweet-Parker model of reconnection. The outflow is limited by a thin slot Δ, which is determined by Ohmic diffusivity. The other scale is an astrophysical scale $L \gg \Delta$. *Middle panel*: Turbulent reconnection model that accounts for the stochasticity of magnetic field lines. The outflow is limited by the diffusion of magnetic field lines, which depends on field line stochasticity. *Bottom panel*: 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 come together.

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.

One of the ways to increase the reconnection rate is to 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). A general review of astrophysical magnetic reconnection theory can be found in Priest & Forbes (2003).

Petschek-type reconnection can survive in the presence of a localized increase of effective resistivity, which can happen due to various plasma effects. For instance, recent years have been marked by a substantial progress in simulations of collisionless reconnection (see Shay & Drake 1998; Bhattacharjee et al. 2003; Drake et al. 2006a, and references therein). This work indicates that under some circumstances a kind of standing whistler mode can stabilize an X-point reconnection region. However, these studies have not demonstrated the possibility of fast reconnection for generic field geometries. They assume that there are no bulk forces acting to produce a large scale current sheet, and that the magnetized regions are convex, which minimizes the energy required to spread the field lines. In addition, the requirements on the media being collisionless are rather strict, for instance, estimates in the literature (see Uzdensky 2006; Yamada et al. 2006) suggest that the L_x should not exceed approximately 50 electron mean free paths. This makes the model not applicable to many astrophysical environments, e.g. to the interstellar medium.

In any case, while the researchers argue whether Hall MHD or a fully kinetic description (Daughton 2006) is necessary, one statement is definitely true: if magnetic reconnection is only fast in collisionless environments, most of the MHD simulations, e.g., of interstellar medium, accretion disks, stars, where the environment is collisional, are in error. We shall argue below that this radical conclusion may not be true and the reconnection is also fast in most astrophysical collisional environments.

3. EFFECTS OF MAGNETIC STOCHASTICITY ON RECONNECTION

3.1. *Earlier Attempts*

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, they are not sufficient to produce reconnection speeds comparable to the Alfvén speed in most astrophysical environments.

"Hyper-resistivity" (Strauss 1985; Bhattacharjee & Hameiri 1986; Hameiri & Bhrattacharjee 1987; Diamond & Malkov 2003) is a more subtle attempt to derive fast reconnection from turbulence within the context of mean-field resistive MHD. The 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. The most important objection to this approach is that by adopting a mean-field approximation one is already assuming some sort of small-scale smearing effect, equivalent to fast reconnection. Furthermore, the integration by parts involves assuming a large scale magnetic helicity flux through the boundaries of precisely the form required to drive fast reconnection. Straus (1988) partially circumvented the first 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 (see Matthaeus & Lamkin 1985).

3.2. *Model in Lazarian & Vishniac 99*

The model of reconnection proposed in Lazarian & Vishniac (1999, henceforth LV99) is a natural generalization of the Sweet-Parker model (see Figure 1). The problem of the Sweet-Parker model is that the reconnection is negligibly slow for any realistic astrophysical conditions. However, astrophysical magnetic fields are generically turbulent.

LV99 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 Figure 1).

To do quantiative estimates one has to adopt the model of MHD turbulence. Such a model for realistic compressible fluids may be constructed on the basis of the Goldreich-Sridhar (1995, henceforth GS95) model of incompressible turbulence (see Cho & Vishniac 2000; Maron & Goldreich 2001; Lithwick & Goldrech 2001; Cho, Lazarian, & Vishniac 2002; Cho & Lazarian 2002, 2003). The most important properties, in terms of magnetic reconnection are those of the Alfvénic modes, which determine field wandering as shown in LV99.

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 Figure 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 Figure 1), which is the scale over which a magnetic field line deviates from its original direction by the thickness of the Ohmic diffusion layer $\lambda_\perp^{-1} \approx \eta/V_{\mathrm{rec,local}}$. 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 it is taken into account that ϕ does depend on scale. Therefore the *local* reconnection rate $V_{\mathrm{rec,local}}$ is given by the usual Sweet-Parker formula but with $\lambda_\parallel$ instead of L_x, i.e. $V_{\mathrm{rec,local}} \approx V_A(V_A\lambda_\parallel/\eta)^{-1/2}$. It is obvious from Figure 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 $V_{\mathrm{rec,global}} \approx V_A(L_x/\lambda_\parallel)(V_A\lambda_\parallel/\eta)^{-1/2}$. 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 GS95 model of MHD turbulence providing the upper limit on the reconnection speed:

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

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 not to impede the reconnection. As a result, LV99 concludes that (1) is not only an upper limit, but is the best estimate of the speed of reconnection. The thick plasma outflows observed during the 2003 November 4 Coronal Mass Ejection reported in Ciaravella & Raymond (2008) are also consistent with the LV99 model.

3.3. *Generalizing the model for partially ionized gas*

A partially ionized plasma fills a substantial volume within our galaxy and the earlier stages of star formation take place in a largely neutral medium. This motivates our study of the effect of neutrals on reconnection. The role of ion-neutral collisions is not trivial. On one hand, they may truncate the turbulent cascade, reducing the small scale stochasticity and decreasing the reconnection speed. On the other hand, the ability of neutrals to diffuse perpendicular to magnetic field lines allows for a broader particle outflow and enhances reconnection rates.

Reconnection in partially ionized gases before the introduction of the LV99 model looked hopelessly slow. For instance, in Vishniac & Lazarian (1999, henceforth VL99) we studied the diffusion of neutrals away from the reconnection zone assuming anti-parallel magnetic field lines The ambipolar reconnection rates obtained in VL99, 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 (VL99; see also Heitsch & Zweibel 2003a,b). 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, the implication is that reconnection and ambipolar diffusion do not change reconnection speed significantly.

Lazarian, Vishniac, & Cho (2004, henceforth LVC04) presented a model of turbulence in a partially ionized gas. This model agrees well with numerical simulations available as the limiting case which can be characterized by one fluid with a high Prandtl number (see Cho et al. 2002, 2003). Using this model LVC04 described field wandering, which is the core of the LV99 model of reconnection. They showed that the magnetic reconnection proceeds fast both in diffuse interstellar and molecular cloud partially ionized gas.

4. FIRST ORDER FERMI ACCELERATION INDUCED BY STOCHASTIC RECONNECTION

In Sweet-Parker model the reconnection can accelerate charged particles, e.g. due to the electric field in the reconnection region. However, the speed of Sweet-Parker reconnection is negligible for most astrophysical environments, thus the transfer of energy from the magnetic field to particles is absolutely negligible, if the reconnection follows the Sweet-Parker predictions.

It is interesting to notice that the first-order Fermi acceleration process is intrinsic to the LV99 model of reconnection. To understand it consider a particle entrained on a reconnected magnetic field line (see Figure 2). This particle may bounce back and forth 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 (de Gouveia Dal Pino & Lazarian 2001, 2003, 2005; Lazarian 2005).

Another way of understanding the acceleration of energetic particles in the reconnection process above is to take into account that the length of magnetic field lines is decreasing during reconnection. As a result, the physical volume of the energetic particles entrained on the field lines is shrinking. Thus, due to Louiville theorem, their momentum should increase to preserve the constancy of the phase volume.

An interesting property of this mechanism that potentially can be used to test the acceleration observationally is that the resulting spectrum of accelerated particles is different from that arising from a shock. Gouveia Dal Pino & Lazarian (2003, 2005) used this mechanism of particle acceleration to explain the synchrotron power-law spectrum arising

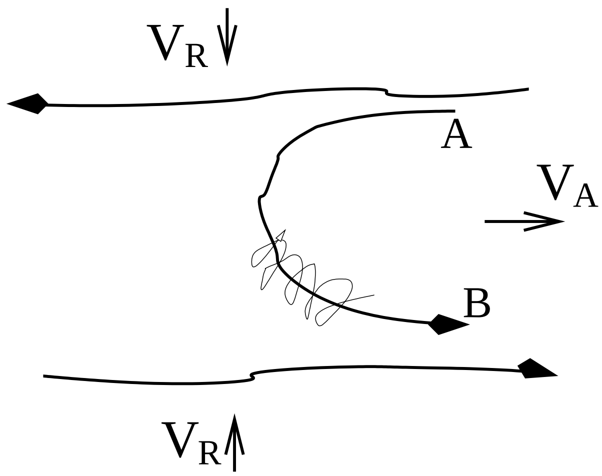

Fig. 2. Cosmic rays spiral about a reconnected magnetic field line and bounce back at points A and B. The reconnected regions move towards each other with the reconnection velocity V_R. The advection of cosmic rays entrained on magnetic field lines happens at the outflow velocity, which is in most cases of the order of V_A. Bouncing at points A and B happens either because of streaming instability or turbulence in the reconnection region (from Lazarian 2005).

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.

The mechanism is similar to the acceleration mechanism that was proposed later by Drake et al. (2006b). Drake et al. (2006b) considered the acceleration of electrons and, similarly, to the Matthaeus, Ambrosiano & Goldstein (1984), assumed that the acceleration happens within 2D contracting loops. While for LV99 model of reconnection the generic configuration of magnetic field are contracting spirals this does not induce a radical difference between the processes. The difference in the spectrum of accelerated particles obtained by Drake et al. (2006b) and that obtained by us stems from the fact that in the former paper the strong backreaction of the accelerated electrons was assumed. However, depending on the environment, this backreaction may vary, resulting in variations of the spectral slopes. Further studies of the acceleration process (see Figure 2) are necessary.

5. FLARES INDUCED BY STOCHASTIC RECONNECTION

If turbulence can drive reconnection, which in turn transforms magnetic energy into kinetic energy, then it seems appropriate to wonder if the process can be self-sustaining. That is, given a very small level of ambient turbulence, how likely is it that reconnection will speed up as it progresses, without any further input from the surrounding medium? A detailed examination of this is beyond the scope of current calculations, but we can clarify this with a simple physical model.

Let's consider a reconnection region of length L and thickness Δ. The thickness is determined by the diffusion of field lines, which is in turn determined by the strength of the turbulence in the volume. Reconnection will allow the magnetic field to relax, creating a bulk flow. However, since stochastic reconnection is expected to proceed unevenly, with large variations in the current sheet, we can expect that some unknown fraction of this energy will be deposited inhomogeneously, generating waves and adding energy to the local turbulent cascade. We take the plasma density to be approximately uniform so that the Alfvén speed and the magnetic field strength are interchangeable. The nonlinear dissipation rate for waves is

$$\tau^{-1}_{\mathrm{nonlinear}} \sim \min\left[\frac{k_\perp^2 v_{\mathrm{wave}}^2}{k_\parallel V_A}, k_\perp^2 v_{\mathrm{turb}} \lambda_{\parallel,\mathrm{turb}}\right], \quad (2)$$

where the first rate is the self-interaction rate for the waves and the second is the dissipation rate by the ambient turbulence. The important point here is that $k_\perp$ for the waves falls somewhere in the inertial range of the strong turbulence. Eddies at that wavenumber will disrupt the waves in one eddy turnover time, which is necessarily less than L/V_A. The bulk of the wave energy will go into the turbulent cascade before escaping from the reconnection zone. (This zone will radiate waves, for the same reason that turbulence in general radiates waves, but it will not significantly impact that energy budget of the reconnection region.)

We can therefore simplify our model for the energy budget in the reconnection zone by assuming that some fraction ϵ of the energy liberated by stochastic reconnection is fed into the local turbulent cascade. The evolution of the turbulent energy density per area is

$$\frac{d}{dt}\left(\Delta v_{\mathrm{turb}}^2\right) = \epsilon V_A^2 V_{\mathrm{rec}} - v_{\mathrm{turb}}^2 \Delta \frac{V_A}{L}, \quad (3)$$

where the loss term covers both the local dissipation of turbulent energy, and its advection out of the reconnection zone. Since $V_{\rm rec} \sim v_{\rm turb}$ and $\Delta \sim L(v_{\rm turb}/V_A)$, we can rewrite this by defining $\mathcal{M}_A \equiv v_{\rm turb}/V_A$ and $\tau \equiv L/V_A$ so that

$$\frac{d}{d\tau}\mathcal{M}_A^3 \approx \epsilon\mathcal{M}_A - \mathcal{M}^3. \quad (4)$$

If ϵ is a constant then

$$v_{\rm turb} \approx V_A \epsilon^{1/2}\left[1 - \left(1 - \frac{\mathcal{M}_0^2}{\epsilon}\right)e^{-2\tau/3}\right]^{1/2}. \quad (5)$$

This implies that the reconnection rate rises to $\epsilon^{1/2}V_A$ is a time comparable to the ejection time from the reconnection region ($\sim L/V_A$). Given that reconnection events in the solar corona seem to be episodic, with longer periods of quiescence, this implies that either ϵ is very small, for example - dependent on the ratio of the thickness of the current sheet to Δ, or is a steep function of $\mathcal{M}_A$. If it scales as $\mathcal{M}_A$ to some power greater than two then initial conditions dominate the early time evolution.

An alternative route by which stochastic reconnection might be self-sustaining would be in the context of a series of topological knots in the magnetic field, each of which is undergoing reconnection. Now the problem is sensitive to geometry. Let's assume that as each knot undergoes reconnection it releases a characteristic energy into a volume which has the same linear dimension as the distance to the next knot. The density of the energy input into this volume is roughly $\epsilon V_A^2 v_{\rm turb}/L$, where ϵ is the efficiency with which the magnetic energy is transformed into turbulent energy. We have

$$V_A^2 \frac{v_{\rm turb}}{L} \sim \frac{v'^3}{L_k}, \quad (6)$$

where L_k is the distance between knots and v' is the turbulent velocity created by the reconnection of the first knot. This process will proceed explosively if $v' > v_{\rm turb}$ or

$$V_A^2 L_k \epsilon > v_{\rm turb}^2 L. \quad (7)$$

This condition is almost trivial to fulfill. The bulk motions created by reconnection will unavoidably generate significant turbulence as they interact with their surrounding, so ϵ should be of order unity. Moreover the length of any current sheet should be at most comparable to the distance to the nearest distinct magnetic knot. The implication is that each magnetic reconnection event will set off its neighbors, boosting their reconnection rates from $v_{\rm turb}$, set by the environment, to $\epsilon^{1/2}V_A(L_k/L)^{1/2}$ (as long as this is less than V_A). The process will take a time comparable to $L/v_{\rm turb}$ to begin, but once initiated will propagate through the medium with a speed comparable to speed of reconnection in the individual knots. In a more realistic situation, the net effect will be a kind of modified sandpile model for magnetic reconnection in the solar corona and chromosphere. As the density of knots increases, and the energy available through magnetic reconnection increases, the chance of a successfully propagating reconnection front will increase.

6. STOCHASTIC RECONNECTION AND REMOVAL OF MAGNETIC FLUX FROM MOLECULAR CLOUDS

As we mentioned above, Sweet-Parker reconnection is too slow[3], while collisionless Petschek reconnection is not applicable to molecular clouds. At the same time, Shu et al. (2006) showed that magnetic field is being removed from the star-forming cores faster than it is allowed by the standard ambipolar diffusion scenario (see Tassis & Mouschovias 2005). Shu et al. (2007) proposed a mechanism that required efficient reconnection of magnetic loops referring to the "hyper-resistivity" concept. As we discussed earlier, this concept is not self-consistent and problematic at its core. Could the reconnection be done by the mechanism we discuss in the paper?

As we discussed earlier, LVC04 considered magnetic reconnection in partially ionized gas and obtained fast reconnection rates that can be obtained there. Thus, it is suggestive that magnetic field can be removed this way from molecular clouds. Incidentally, this also means that the model of reconnection should be considered for the transport of the angular momentum in protostellar disks (see Lazarian 2005).

7. DISCUSSION AND SUMMARY

The advantage of the model in Lazarian & Vishaniac (1999) is that, first of all, the reconnection is robust and is fast in any type of fluid, provided that the fluid is turbulent enough. The latter requirement is natural for most of astrophysical fluids (see Armstrong et al. 1995). At the same time, the model predicts that if the fluids are not turbulent initially, they should be prone to bursts of reconnection, w hich may provide an appealing explanation of Solar Flares.

7.1. *Self-consistency of the model*

The high speed of reconnection given by equation (1) naturally leads to a question of self-consistency. Is it reasonable to take the turbulent

[3]A modification of the Sweet-Parker model to include ambipolar diffusion cannot generically induce much faster reconnection either (see Vishniac & Lazarian 1999).

cascade suggested in GS95 when field lines in adjacent eddies are capable of reconnecting? It turns out that in this context, our estimate for $V_{\rm rec,global}$ is just fast enough to be interesting. We note that when considering the intersection of nearly parallel field lines in adjacent eddies the acceleration of plasma from the reconnection layer due to the pressure gradient is not $k_\| V_A^2$, but rather $(k_\|^3/k_\perp^2)V_A^2$, since only the energy of the component of the magnetic field which is not shared is available to drive the outflow. On the other hand, the characteristic length contraction of a given field line due to reconnection between adjacent eddies is only $k_\|/k_\perp^2$. This gives an effective ejection rate of $k_\| V_A$. Since the width of the diffusion layer over a length $k_\|^{-1}$ is just $k_\perp^{-1}$, we can replace equation (1) with $V_{\rm rec,global} \approx V_A \frac{k_\|}{k_\perp}$. The associated reconnection rate is just

$$\tau^{-1}_{\rm reconnect} \sim V_A k_\|, \tag{8}$$

which in GS95 is just the nonlinear cascade rate on the scale $k_\|^{-1}$. However, this result is general and does not involve assuming that GS95 is correct. As we discuss below, most of the energy liberated in reconnection goes into motions on length scales comparable to the dimensions of the reconnecting eddies, so this energy release will not short circuit the energy cascade described in GS95. On the other hand, we can invert this argument to see that reconnection can play an important role in preventing the buildup of unresolved knots in the magnetic field. Such structures could play a major role in inhibiting the cascade of energy to smaller scales, flattening the energy spectrum relative to the predictions of GS95. Our conclusion is that such structures will disappear as fast as they appear, supporting the notion that they play a limited role in the dynamics of MHD turbulence.

Finally, we note that if the magnetic field structure is driven by turbulence in another location, as when the footpoints of magnetic arcades are stirred by turbulent motions, then we can evaluate its effects in terms of the amplitude of field stochasticity and the scaling of structure anisotropy with scale. The actual turbulence may be balanced or imbalanced, have or not have "polarization intermittency" (see Beresnyak & Lazarian 2006, 2008) the robust nature of the reconnection implies that the reconnection will be sensitive to the amplitude of the induced field stochasticity, but not the details of the turbulent mixing process.

7.2. *Turbulent diffusivity and dynamo*

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 disk 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. This solve one part of the problem of dynamo. The other part is related to magnetic helicity conservation (see Vishniac et al. 2003).

Interestingly enough, high turbulent diffusivity is also required for advecting heat in astrophysical plasmas, e.g. in clusters of galaxies (see Lazarian 2006). Turbulent reconnection events enable eddies to transfer heat in the way similar to the advection of heat by turbulence in unmagnetized fluid (see Cho et al. 2003).

7.3. *Dissipation of energy*

The usual assumption for energy dissipation in reconnection is that some large fraction of the energy given up by the magnetic field, in this case $\sim \rho V_A^2 L_x^3$, goes into heating the electrons. This is not the case here. Only a fraction, $\sim 1/(k_\| L_x)$ of any flux element is annihilated by Ohmic heating within the reconnection zone. Over the entire course of the reconnection event the efficiency for electron heating is no greater than

$$\epsilon_e \lesssim \frac{\eta/\Delta}{V_{\rm rec,global}} = \frac{V_{\rm rec,local}}{V_{\rm rec,global}} = \frac{1}{k_\| L_x}, \tag{9}$$

or, with GS95 scaling substituted (see LV99)

$$\epsilon_e \lesssim \left(\frac{V_A l}{\eta}\right)^{-2/5} \left(\frac{v_l}{v_A}\right)^{8/5} \left(\frac{l}{L_x}\right)^{4/5}. \tag{10}$$

The electron heating within the current sheet will not be uniform, due to the presence of turbulence, the intermittent presence of reconnected flux, and any collective effects we have neglected here. To the extent that these are important they will also lower the electron heating efficiency by broadening the reconnection layer.

7.4. *Summary*

The results above can be summarized as follows

• Recent successful numerical testing of the model in Lazarian & Vishniac (1999), presented in a companion paper by Kowal et al. (2009) increase the appeal of the model and stimulate studies of its consequencies.

• The aforementioned model of stochastic field reconnection provides justification for many of astrophysical simulations. If, on the contrary, the only reconnection model that works is the collisionless reconnection, this means that most of the numerical simulations, for instance, of interstellar medium are in error. Indeed, in the collisional environments the reconnection speed would be negligible, which cannot be achieved with the numerical simulations.

• The model of magnetic field reconnection in the presence of weak magnetic field stochasticity is a natural generalization of the Sweet-Parker model of reconnection. Its many consequencies include bursts of reconnection, efficient first order Fermi acceleration of energetic particles, efficient diffusion of magnetic field in turbulent plasmas etc.

Research by AL is supported by the NSF grant AST 0808118 and the NSF Center for Magnetic Self-Organization and by EV is supported by the National Science and Engineering Research Council of Canada.

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