Astrophysical Reconnection and Particle Acceleration

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Abstract. Astrophysical reconnection takes place in a turbulent medium. The turbulence in most cases is pre-existing, not caused by the reconnection itself. The model of magnetic reconnection in Lazarian & Vishniac (1999) predicts that in the presence of turbulence the reconnection becomes fast, i.e. it is independent of resistivity, but dependent on the level of turbulence. Magnetic reconnection injects energy into plasmas through a turbulent outflow from the reconnection region and this outflow can enhance the level of turbulence creating bursts of reconnection. Magnetic reconnection in the presence of turbulence can accelerate energetic particles through the first order Fermi mechanism, as was predicted in Gouveia dal Pino & Lazarian (2005). We discuss new numerical results on particle acceleration in turbulent reconnection, compare the acceleration arising from turbulent reconnection to the acceleration of energetic particles in turbulent medium.

1. Reconnection and Numerical Studies

It is generally believed that a magnetic field embedded in a highly conductive fluid preserves its topology for all time due to the magnetic fields being frozen-in (1; 28). Although ionized astrophysical objects, like stars and galactic disks, are almost perfectly conducting, they show indications of changes in topology, “magnetic reconnection”, on dynamical time scales (see 27). Reconnection can be observed directly in the solar corona (e.g. 33), but can also be inferred from the existence of large-scale dynamo activity inside stellar interiors (see 29). Solar flares and $\gamma$-ray bursts (see 22, 34) are usually associated with magnetic reconnection. A lot of previous work has concentrated on showing how reconnection can be rapid in plasmas with very small collisional rates (7; 8), which substantially constrains astrophysical applications of the corresponding reconnection models.

A theory of magnetic reconnection is necessary to understand whether reconnection is represented correctly in numerical simulations. One should keep in mind that reconnection is fast in computer simulations due to high numerical diffusivity. Therefore, if there are situations where magnetic fields reconnect slowly, numerical simulations do not adequately reproduce the astrophysical reality. This means that if collisionless reconnection is indeed the only way to make reconnection fast, then the numerical simulations of many astrophysical processes, including those in interstellar media, which is collisional at the relevant scales, are in error. At the same time, it is not possible to
conclude that reconnection must always be fast on the empirical grounds, as solar flares require periods of flux accumulation time, which correspond to slow reconnection.

To understand the difference between reconnection in astrophysical situations and in numerical simulations, one should recall that the dimensionless combination that controls the resistive reconnection rate is the Lundquist number, defined as $S = L_x V_A / \lambda$, where $L_x$ is the length of the reconnection layer, $V_A$ is the Alfvén velocity, and $\lambda = \eta c^2 / 4\pi$ is Ohmic diffusivity. Because of the huge astrophysical length-scales $L_x$ involved, the astrophysical Lundquist numbers are also huge, e.g., for the ISM they are about $10^{16}$, while present-day MHD simulations correspond to $S < 10^4$. As the numerical efforts scale as $L_x^4$, where $L_x$ is the size of the box, it is feasible neither at present nor in the foreseeable future to have simulations with realistically Lundquist numbers.

2. Reconnection and Turbulence

While astrophysical fluids show a wide variety of properties in terms of their collisionality, degree of ionization, temperature etc., they share a common property, namely, most of the fluids are turbulent. The turbulent state of the fluids arises from large Reynolds numbers $Re \equiv LV/v$, where $L$ is the scale of the flow, $V$ is its velocity and $v$ is the viscosity, associated with astrophysical media. Note, that the large magnitude of $Re$ is mostly the consequence of the large astrophysical scales $L$ involved as well as the fact that (the field-perpendicular) viscosity is constrained by the presence of magnetic field.

Observations of the interstellar medium reveal a Kolmogorov spectrum of electron density fluctuations (see 2; 4) as well as steeper spectral slopes of supersonic velocity fluctuations (see 21 for review). Measurement of the solar wind fluctuations also reveal turbulence power spectrum (24). Ubiquitous non-thermal broadening of spectral lines as well as measures obtained by other techniques (see 3; 11) confirm that turbulence is present everywhere we test for its existence. As turbulence is known to change many processes, in particular the process of diffusion, the natural question is how it affects magnetic reconnection.

To deal with strong, dynamically important magnetic fields Lazarian & Vishniac (21, henceforth LV99) proposed a model of fast reconnection in the presence of sub-Alfvénic turbulence. It is important to stress that unlike laboratory controlled settings, in astrophysical situations turbulence is preexisting, arising usually from the processes different from reconnection itself. In fact, any modeling of astrophysical reconnection should account for the fact that magnetic reconnection takes place in the turbulent environment and in most cases the turbulence does not arise from magnetic reconnection. The analogy here can be as follows: turbulence that is experienced by the plane does not arise from the plane motion, but preexist in the atmosphere.

LV99 identified stochastic wandering of the magnetic field-lines as the most critical property of MHD turbulence which permits fast reconnection and obtained analytical relations between the reconnection rate and the turbulence intensity and the turbulence injection scale.

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1 The magnetic Reynolds number, which is the ratio of the magnetic field decay time to the eddy turnover time, is defined using the injection velocity $v_I$ as a characteristic speed instead of the Alfvén speed $V_A$, which is taken in the Lundquist number.
Reconnection and Acceleration

Figure 1. Left panel. Sweet-Parker model versus the model in LV99. Turbulence makes the outflow region much wider and independent of resistivity. From (23).
Right panel. Acceleration of energetic particles as the magnetic field shrinks as the result of reconnection. From Lazarian 2005.

It worth noting that the LV99 model (see Fig. 1, left panel) is radically different from its predecessors which also appealed to the effects of turbulence. For instance, unlike (32) and (13) Jacobson (1984) the model does not appeal to changes of the microscopic properties of the plasma. The nearest progenitor to LV99 was the work of (25, 26), who studied the problem numerically in 2D MHD and who suggested that magnetic reconnection may be fast due to a number of turbulence effects, e.g. multiple X points and turbulent EMF. However, (25, 26) did not realize the key role played by magnetic field-line wandering, and did not obtain a quantitative prediction for the reconnection rate, as did LV99.

LV99 revealed a very intimate relation between turbulence and magnetic reconnection. First of all, it shows that reconnection is a necessary ingredient of MHD turbulence, this is the process that makes the currently accepted picture of MHD turbulence (12) self-consistent. Moreover, further research in Eyink et al. (9, henceforth ELV11) revealed that the expressions of reconnection rate in LV99 can be obtained from the basic fluid turbulence concept of Richardson diffusion.

3. Reconnection and Plasma effects

For years plasma effects have been considered essential for fast magnetic reconnection. On the contrary, LV99 makes use of the MHD approximation. This raises the issue to what extend the LV99 model is applicable to astrophysical plasmas.

An MHD description of plasmas has been revisited recently in ELV11. There three characteristic length-scales were considered: the ion gyroradius $\rho_i$, the ion mean-free-path length $\ell_{mfp,i}$, and the scale $L$ of large-scale variation of magnetic and velocity fields. Astrophysical plasmas are in many cases “strongly collisional” in the sense that $\ell_{mfp,i} \ll \rho_i$, which is the case for the interiors of stars and accretion disks. In such cases, a fluid description of the plasma is valid. In the “weakly collisional” $\ell_{mfp,i} \gg \rho_i$. The ratio

$$\frac{\ell_{mfp,i}}{\rho_i} \propto \Lambda \frac{v_A}{\ln \Lambda / c},$$

follows from the standard formula for the Coulomb collision frequency (see (?), eq.(1.25)). Here $\Lambda = 4\pi n\lambda_D^3$ is the plasma parameter, or number of particles within
the Debye screening sphere. When astrophysical plasmas are very weakly coupled (hot and rarefied), then $\Lambda$ is large, e.g., of the order of $10^9$ or more for the warm component of the interstellar medium or solar wind (see Table 1 in ELV11). For such ratio the expansion over small ion Larmor radius $\rho_i$ provides “kinetic MHD equations” which differ from the standard MHD by having anisotropic pressure tensor.

Plasmas that are not strongly collisional can be divided into two cases: “collisionless” plasmas for which $\ell_{mf,i} \gg L$, the largest scales of interest, and “weakly collisional” plasmas for which $L \gg \ell_{mf,i}$. In the latter case the “kinetic MHD” description can be further reduced in complexity at scales greater than $\ell_{mf,i}$ (see ELV11). This reproduces a fully hydrodynamic MHD description at those scales. For instance, the warm ionized ISM is “weakly collisional”, while post-CME current sheets and the solar wind impinging on the magnetosphere are “collisionless.”

Plasmas that are not strongly collisional further divide into two cases: “collisionless” plasmas for which $\ell_{mf,i} \gg L$, the largest scales of interest, and “weakly collisional” plasmas for which $L \gg \ell_{mf,i}$. In the latter case the “kinetic MHD” description can be further reduced in complexity at scales greater than $\ell_{mf,i}$ (see ELV11). This reproduces a fully hydrodynamic MHD description at those scales, with anisotropic transport behavior associated to the well-magnetized limit. Among our examples in Table 1 above, the warm ionized ISM is “weakly collisional”, while post-CME current sheets and the solar wind impinging on the magnetosphere are close to being “collisionless.”

Additional important simplifications occur if the following assumptions are satisfied: turbulent fluctuations are small compared to the mean magnetic field, have length-scales parallel to the mean field much larger than perpendicular length-scales, and have frequencies low compared to the ion cyclotron frequency. These are standard assumptions of the (12) theory of MHD turbulence. They are the basis of the “gyrokinetic approximation” (30; 31). At length-scales larger than the Larmor radius $\rho_i$, another reduction takes place. The incompressible shear-Alfven wave modes exhibit dynamics independent of compressive motions and can be described by the “Reduced MHD” (RMHD) equations (see 12; 5). This fact is essential for the LV99 justifying the use of the treatment based on an incompressible MHD model.

Within the LV99 model, the reconnection rate is determined by large scale magnetoc wandering (see Figure 1), while small scale plasma effects may change the local reconnection which are irrelevant for the global reconnection at least in the fully ionized plasma (see 23). This conclusion is supported by simulations in (14) where plasma effect were simulated by using anomalous resistivity. We should mention that although plasma effects do not change the global reconnection rate, can be important for the acceleration of electrons.

While Hall MHD is a default for many researchers, ELV11 showed that the effects of the Hall term on the field wandering is negligible on scales larger than $\rho_i$ even if the Hall term in the generalized Ohm equation is dominant.

4. Reconnection and Particle Acceleration

Magnetic reconnection results in shrinking of magnetic loops and the charged particles entrained over magnetic loops get accelerated (see Figure 1, right panel). This process was proposed in de Gouveia dal Pino & Lazarian (6, henceforth GL05) (see also Lazarian 2005, 2006) for the LV99 reconnection and then was adopted for the collisionless
reconnection in \cite{8}. The physics of the acceleration is the same although GL05 appealed to the 3D magnetic bundles (see Figure 1), while \cite{8} considered 2D shrinking islands. The latter is the consequence of the constrained 2D geometry and they present a strongly degenerate case in 3D. The difference in dimensions affects the acceleration efficiency according to \cite{15}.

GL05 claimed that the acceleration is of the first order Fermi type. This was tested recently in \cite{16}. Below we describe the numerical set up and the results of calculations.

In order to integrate the test particle trajectories we freeze in time a data cube obtained from the MHD models of reconnection and turbulence performed in \cite{14} and inject test particles in the domain with random initial positions and directions and with an initial thermal distribution. For each particle we solve the relativistic motion equation

\[
\frac{d}{dt}(\gamma m_0 u) = q(E + u \times B),
\]

where \(m_0, q\) and \(u\) are the particle mass, electric charge and velocity, respectively, \(E\) and \(B\) are the electric and magnetic fields, respectively, \(\gamma \equiv \left(1 - \frac{u^2}{c^2}\right)^{-\frac{1}{2}}\) is the Lorentz factor, and \(c\) is the speed of light. The electric field \(E\) is taken from the MHD simulations \(E = -v \times B + \eta J\), where \(v\) is the plasma velocity, \(J \equiv \nabla \times B\) is the current density, and \(\eta\) is the Ohmic resistivity coefficient. We neglect the resistive term above since its effect on particle acceleration is negligible \cite{15}.

In Figure 2 we present the time evolution of the kinetic energy of the particles which have their parallel and perpendicular (red and blue points, respectively) velocity components accelerated for three models of reconnection. The upper left panel shows

![Figure 2](image)
the energy evolution for a 2D model without the guide field (as in the models studied
in the previous sections). Initially, the particles pre-accelerate by increasing their per-
pendicular velocity component only. Later we observe an exponential growth of energy
mostly due to the acceleration of the parallel component which stops after the energy
reaches values of $10^3$–$10^4 \ m_p$ (where $m_p$ is the proton rest mass energy). Further on,
particles accelerate their perpendicular component only with smaller linear rate in a log-
log diagram. In 2D case, there is also an initial slow acceleration of the perpendicular
component followed by the exponential acceleration of the parallel velocity component.
Due to the presence of a weak guide field, the parallel component accelerates further to
higher energies at a similar rate as the perpendicular one. This implies that the presence
of a guide field removes the restriction seen in the 2D model without a guide field and
allows the particles to increase their parallel velocity components as they travel along
the guide field, in open loops rather than in confined 2D islands. This result is reassured
by the 3D model in the bottom panel of Figure 2 where no guide field is necessary as
the MHD domain in fully three-dimensional. In this case, we clearly see a continu-
ous increase of both components, which suggests that the particle acceleration behavior
changes significantly when 3D effects are considered, where open loops replace the
closed 2D reconnecting islands.

5. Conclusions

The results of these studies can be very briefly summarized as follows:

1. Advances in the understanding of magnetic reconnection in the MHD regime,
in particular, turbulent magnetic reconnection in (20) model motivates the studies of
whether the reconnection in this regime can accelerate energetic particles.

2. Contracting magnetic loops in magnetic reconnection in 2D, in the MHD
regime, provides the acceleration analogous to that observed in PIC simulations, which
proves that the acceleration in reconnection regions is a universal process which is not
determined by the details of plasma physics.

3. Acceleration of energetic particles in 2D and 3D shows substantial differences,
which call for focusing on realistic 3D geometries of reconnection. Our study also
shows that apart from the first order Fermi acceleration, additional acceleration pro-
cesses may occur within reconnection sites.

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