

Acceleration of Energetic Particles through Reconnection of Weakly Stochastic Magnetic Field

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Abstract Astrophysical media are turbulent and therefore reconnection should be treated in the presence of pre-existing turbulence. We consider the model of fast magnetic reconnection in Lazarian and Vishniac (Astrophys J 517:700–718, 1999) which predicts that the rate of reconnection is controlled by the intensity and the injection scale of turbulent motions. We provide new evidence of successful testing of the model and argue that the model presents a generic set up for astrophysical reconnection events. We study particle acceleration that takes place in volumes of driven turbulence as well turbulent volumes in the presence of large scale reconnection. We show that in the latter case the acceleration is of the first order Fermi type thus supporting the model of acceleration proposed in Gouveia dal Pino and Lazarian (Astron Astrophys 44:845–853, 2005)

1 Introduction

Astrophysical fluids are turbulent and this changes the physics of many processes. It has been long accepted that this dramatically alters the nature of the cosmic ray propagation and acceleration (see [32]), the research during the last decade also testifies that the nature of the reconnection process is being radically changed

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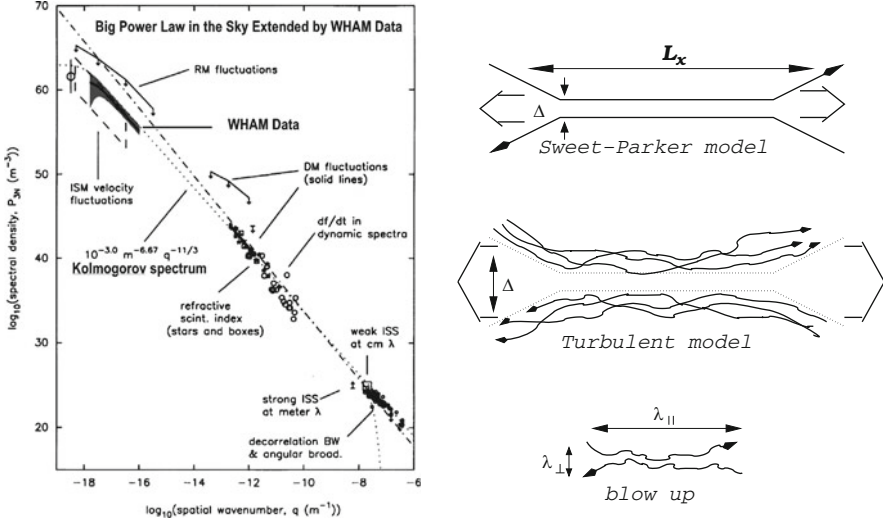


Fig. 1 *Left panel:* Turbulence in the interstellar gas as revealed by electron density fluctuations. “Big Power Law in the Sky” in Armstrong et al. [2] extended using WHAM data. The slope corresponds to that of Kolmogorov turbulence (Modified from [5]). *Right Panel:* Sweet-Parker model versus the model in LV99. Turbulence makes the outflow region much wider and independent of resistivity (From Lazarian et al. [28])

[26], henceforth LV99, [18, 19]). Reconnection in turbulent media was invoked by de Gouveia dal Pino and Lazarian ([8], henceforth GL05) in the model of the first order Fermi acceleration of cosmic rays in reconnection sites. This paper discusses new testings of the LV99 model as well as new results on energetic particle acceleration in the regions of reconnection of weakly turbulent magnetic field.

Astrophysical turbulence, in general, is *not* caused by reconnection. Therefore, while dealing with problems of reconnection and related particle acceleration it is proper to treat the turbulence as pre-existing. For instance, it has been known for decades that interstellar medium (ISM) is driven by violent supernovae explosions (McKee and Ostriker 1977). By now it has been accepted that the ISM is turbulent on scales ranging from AUs to kpc (see [2, 14, 24]). Figure 1 shows the turbulent power density plotted against the inverse of the scale length, with data at large scales, i.e. at small wavenumbers q expanded using the Wisconsin H_α Mapper (WHAM) data on electron density fluctuations [5]. Another example is turbulence is solar wind (see [31]).

The problem of magnetic reconnection is a long standing one. 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 (see [1]). At the same time, although ionized astrophysical objects, like stars and galactic disks, are almost perfectly conducting, they show indications of changes in topology [38],

“magnetic reconnection”, on dynamical time scales (see [37]). Reconnection can be observed directly in the solar corona [43], but can also be inferred from the existence of large-scale dynamo activity inside stellar interiors [39]. Solar flares are usually associated with magnetic reconnection. More recent research shows that γ -ray bursts can also have a similar origin [27, 44].¹ At the same time, a lot of previous work has concentrated on showing how reconnection can be rapid in plasmas with very small collisional rates (see [12, 13]). We feel that this substantially constrains astrophysical applications of the corresponding reconnection models.

Magnetic reconnection presents a known example of flux freezing violation, but it is conceivable that it was not taken seriously due to the unclear nature of fast reconnection (see [46] and references therein). Indeed, for years it was considered that fast reconnection required some special physical conditions and therefore “flux freezing” is fulfilled everywhere apart from some special zones.

The understanding of flux freezing in turbulent astrophysical environments has been challenged relatively recently and not all the consequences of this radical change have been evaluated so far. LV99 identified magnetic field wandering, which is the inherent property of magnetized turbulent plasma, as the cause of fast, i.e. independent of resistivity, magnetic reconnection. They showed that in turbulent fluids magnetic fields should undergo constant reconnection and change their identity all the time. This implies that magnetic fields are not any more frozen into a perfectly conducting fluid if this fluid is turbulent as was explicitly stated first in Vishniac and Lazarian (1999). Later, the challenge to the concept of “flux freezing” came from another side, i.e. from more formal mathematical studies of turbulent magnetic fields (see Eyink et al. 2011). Eyink et al. ([15], henceforth ELV11) showed the consistency of these two approaches and established the equivalence of the LV99 treatment with that in more recent mathematical papers.

While the idea that turbulence can change the reconnection rates has been discussed in a number of earlier papers, the LV99 model was radically different from its predecessors. For instance, Mathaeus and Lamkin [35, 36] performed 2D numerical simulations of turbulence and provided arguments in favor of magnetic reconnection getting fast. However, the physics of the processes that they considered was very different from that in LV99. For instance, the key process of field wandering of the LV99 model was not considered in Mathaeus and Lamkin [35, 36]. On the contrary, the components of their approach, e.g. X-point and possible effects of heating and compressibility are not ingredients of the LV99 model. Other papers, e.g. [17, 41] explore the changes of the microscopic properties of the plasma induced by turbulence and consider how these changes can accelerate magnetic reconnection. LV99 shows that the microscopic plasma properties are irrelevant for their model of reconnection (see testing in [18] and more discussion of plasma effects in ELV11).

¹LV99 model of reconnection predicts the bursty character of reconnection when the initial state of magnetic field is close to the laminar one.

In what follows, we discuss the LV99 model in Sect. 2, present new numerical tests of the LV99 model in Sect. 3, demonstrate the efficiency of energetic particle acceleration in turbulent reconnection regions in Sect. 4. In Sect. 5 we present astrophysical settings where we identified the acceleration of particles in reconnection layers, in Sects. 6 and 7 we, respectively, provide the discussion and summary of our results.

2 Reconnection of Weakly Turbulent Magnetic Field

To deal with strong, dynamically important magnetic fields 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 [6]. In fact, any modeling of astrophysical reconnection should account for the turbulent state of fluids 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 airplane does not arise from the airplane 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.

LV99 revealed a very intimate relation between turbulence and magnetic reconnection and this connection was deepened by later research (ELV11, [22]). First of all, LV99 showed that reconnection was a necessary ingredient of MHD turbulence, this was the process that made the currently accepted picture of MHD turbulence in [16] self-consistent. Moreover, further research in ELV11 revealed that the expressions of reconnection rate in LV99 can be obtained from the concept of Richardson diffusion, which is the basic concept of fluid turbulence.

3 Numerical Testing of LV99 Model

Testing of LV99 model of reconnection was performed in [18,19]. Below we present some of the results obtained. In Fig. 2 we see the results for varying amounts of input power, for fixed resistivity and injection scale as well as for the case of no turbulence at all. The line drawn through the simulation points is for the LV99 predicted scaling, i.e. $V_{rec} \sim P^{1/2}$, where P is the power of injected turbulence. We also see the results obtained with a new way of real space turbulence driving (see more in [19]). This driving is different from the Fourier space in [18]. The results with both types of driving support LV99 model. In addition, Kowal et al. [18]

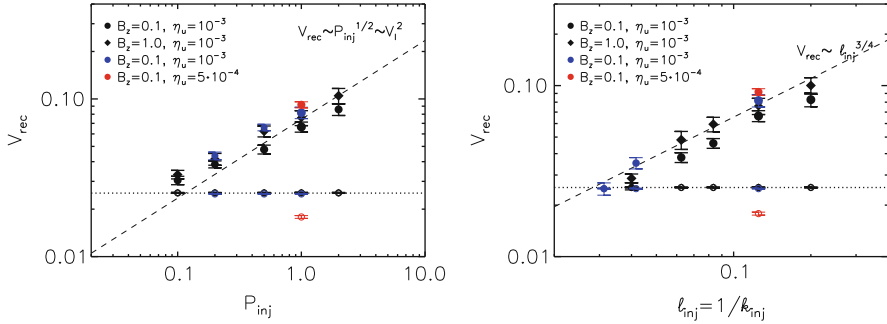


Fig. 2 New and old testing of LV99 model. *Left Panel:* The dependence of the reconnection speed V_{rec} on P_{inj} . *Blue symbols* show models with new driving in which the eddies were injected in magnetic field instead of velocity, as in the previous models (*black symbols*). A unique *red symbol* shows the reconnection rates from model with new driving in velocity performed with higher resolution ($512 \times 1024 \times 512$) and resistivity coefficient reduced to $\eta_u = 5 \cdot 10^{-4}$. *Right Panel:* The dependence of the reconnection speed V_{rec} on l_{inj} with additional models in which turbulence was driven in a new way as we describe in the text. Error bars represent the time variance of V_{rec} . The size of symbols corresponds to the error of V_{rec} (From Kowal et al. [19])

confirmed the predicted independence of the rate of reconnection on both Ohmic and anomalous resistivities, supporting LV99 conclusion that the reconnection is determined only by the properties of the turbulent flow.

4 Reconnection and Particle Acceleration

Magnetic reconnection results in shrinking of magnetic loops which induces the charged particles entrained on magnetic loops to get accelerated (see Fig. 3). This process was proposed in GL05 for the LV99 reconnection and then was adopted for the collisionless reconnection in [13]. The physics of the acceleration is the same although GL05 appealed to the 3D magnetic bundles (see Fig. 3), while [13] considered 2D shrinking islands. The latter is an artifact of the constrained 2D geometry. The difference in dimensions affects the acceleration efficiency according to [20]. GL05 claimed that the acceleration is of the first order Fermi type. This was confirmed in [21]. 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 in [18] and inject test thermal particles in the domain with random initial positions and directions. For each particle we solve the relativistic motion equation

$$\frac{d}{dt}(\gamma mu) = q(\mathbf{E} + \mathbf{u} \times \mathbf{B}), \quad (1)$$

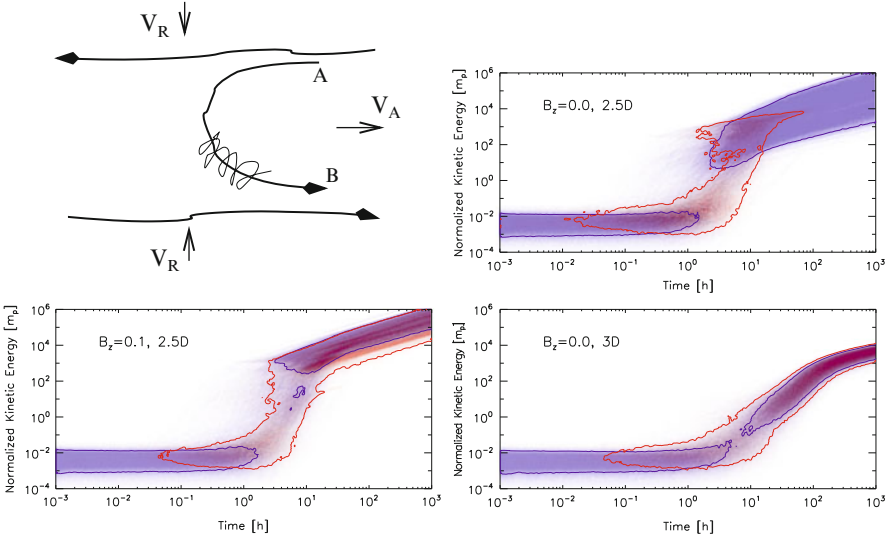


Fig. 3 *Left upper corner*: Schematic of the first order Fermi acceleration in the process of reconnecting turbulent magnetic field (From Lazarian 2005). *Other panels*. Numerical studies of particle acceleration. Kinetic energy evolution of a group of 10^4 protons in 2D models of reconnection with a guide field $B_z = 0.0$ and 0.1 . In the *right bottom panel* a fully 3D model with initial $B_z = 0.0$ is presented. The colors show how the parallel (red) and perpendicular (blue) components of the particle velocities increase with time. The contours correspond to values 0.1 and 0.6 of the maximum number of particles for the parallel and perpendicular accelerations, respectively. The energy is normalized by the rest proton mass energy. The background magnetized flow with multiple current sheet layers is at time 4.0 in Alfvén time units (From Kowal et al. [20])

where m , q and \mathbf{u} are the particle mass, electric charge and velocity, respectively, \mathbf{E} and \mathbf{B} are the electric and magnetic fields, respectively, $\gamma \equiv (1 - u^2/c^2)^{-1}$ is the Lorentz factor, and c is the speed of light. The electric field \mathbf{E} is taken from the MHD simulations $\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta \mathbf{J}$, where \mathbf{v} is the plasma velocity, $\mathbf{J} \equiv \nabla \times \mathbf{B}$ is the current density, and η is the Ohmic resistivity coefficient. We neglect the resistive term above since its effect on particle acceleration is negligible [20].

In Fig. 3, 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 the energy evolution for a 2D model without the guide field. Initially, the particles pre-accelerate by increasing their perpendicular 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 2.5D 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 Fig. 3, where no guide field is necessary as the MHD domain is fully three-dimensional. In this case, we clearly see a continuous 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 Reconnection and Acceleration: Astrophysical Examples

Lazarian and Opher [25] identified the origin of anomalous cosmic rays measured by Voyagers as arising from magnetic reconnection in heliosheath. As magnetic field lines of the magnetic spiral (arising from solar rotation) present in the solar wind get closer together magnetic reconnection is expected. In view of solar wind being turbulent, the LV99 model of reconnection is relevant.²

To explain the excess of the cosmic ray arrival from the direction towards heliotail Lazarain and Desiati (2010) considered magnetic reconnection in heliotail. The accumulation of magnetic flux of opposite polarities in heliotail arises from solar magnetic field reversals within 11 year cycle. Magnetic fields in heliotail are expected to be turbulent. The mechanism provides an attractive alternative to those discussed in the literature.

Magnetic reconnection in clusters of galaxies present an interesting way of accelerating energetic particles there (see Lazarian and Brunetti 2011). The large scale reversals of magnetic fields in galaxy clusters are expected as a result of accretion flows, instabilities and galactic jets. Acceleration in reconnection regions may present an appealing alternative to the acceleration of cosmic rays by the intracluster magnetic turbulence. Further work on the quantitative elaboration of the predictions of this and other astrophysical models that appeal to the acceleration of cosmic rays in reconnection sites are necessary [23].

6 Discussion

First of all, we would like to stress that the LV99 model is not in conflict with the studies of magnetic reconnection in collisionless plasmas that have been a major thrust of the plasma physics community (e.g. Daughton et al. [9]). Unlike latter

²Drake (2001) followed with a model appealing to the collisionless reconnection for which turbulence is not directly involved.

studies, LV99 deals with turbulent environments. It is demonstrated in LV99, the local reconnection rates are influenced by plasma effects, e.g. kinetic effects of Hall effects, but the overall or global reconnection rate, i.e. the rate at which magnetic flux tubes reconnect, is determined by the turbulent broadening of the reconnection region. Thus, in the turbulent astrophysical media the rate of reconnection is not going to be affected by additional mechanisms.

Over the last decade, more traditional approaches to reconnection have changed considerably. At the time of its introduction, the models competing with LV99 were modifications of the single X-point collisionless reconnection scheme first introduced by Petschek [40]. Those models had point-wise localized reconnection regions which were stabilized via plasma effects so that the outflow opened up on larger scales. Such configurations would be difficult to sustain in the presence of random forcing, which would be expected to collapse the reconnection layer. Moreover, [7] argued that observations of solar flares were inconsistent with single X-point reconnection.

In response to these objections, more recent models of collisionless reconnection have acquired several features in common with the LV99 model. In particular, they have moved to consideration of volume-filling reconnection, (although it is not clear how this volume filling is achieved in the presence of a single reconnection layer (see [13])). While much of the discussion still centers around magnetic islands produced by reconnection, in three dimensions these islands are expected to evolve into contracting 3D loops or ropes due to tearing-type instabilities in electron-current layers [10, 11]. This is broadly similar to what is depicted in Fig. 1, at least in the sense of introducing stochasticity to the reconnection zone. At the same time, although the 3D PIC simulation studies are described as “turbulent”, they do not exhibit the inertial-range power-law spectra observed in the magnetosphere and do not take into account either the pre-existing turbulence found in many of its regions (due to temperature anisotropy, velocity shear, Kelvin-Helmholtz instability, etc.) or inertial-range turbulence generated as a consequence of reconnection itself [45].

The above remarks apply to the recent 3D PIC study [4], which observes micro-turbulence in the electron current layer during reconnection. The authors identify the source of this “turbulence” as a filamentation instability driven by current gradients, very similar to a related instability in the Electron MHD (EMHD) model. The key aim of this work was to identify the term in the generalized Ohm’s law which supplies the reconnection electric field to break the “frozen-in” condition. However, this study ignores the ambient inertial-range turbulence observed in the magnetosphere and other astrophysical plasmas, which may strongly modify laminar instabilities and reconnection process.

We believe that in most astrophysical situations one has to deal with the *pre-existing turbulence*, which is the inevitable consequence of the high Reynolds number of astrophysical fluids and for which abundant empirical evidence exists. Such turbulence may modify or suppress instabilities, e.g. the tearing mode instability invoked in many studies [3, 33]. At the same time, LV99 model induces fast reconnection on dynamical time scales.

Our study shows that the acceleration of energetic particles in LV99-type reconnection layers provides first order Fermi acceleration first described in de GL05. The studies in [19, 20] confirm the promise of this way of accelerating of particles in various environments.

7 Summary

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

1. Advances in the understanding of magnetic reconnection in the MHD regime, in particular, related to the LV99 model of turbulent magnetic reconnection motivate the studies of whether the reconnection in this regime can accelerate energetic particles. New higher resolution testing of the LV99 model as well as simulations with a different type of driving confirm that the reconnection is fast.
2. Contracting magnetic loops in magnetic reconnection in 2D, in the MHD regime, provide 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. This confirms that the process of acceleration in GL05 and Drake et al. (2006) has the same nature.
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 the first order Fermi acceleration dominates the second order Fermi that is also present in turbulent reconnection layers.

Acknowledgements The research of AL is supported by the Center for Magnetic Self-Organization in Laboratory and Astrophysical Plasmas. AL also acknowledged Humboldt Award at the Universities of Cologne and Bochum, as well as the hospitality of the International Institute of Physics (Brazil) and the Vilas Associate Award. GK and EMGDP acknowledge the support by the FAPESP grants no. 2006/50654-3 and 2009/50053-8, and the CNPq grant no. 300083/94-7. This research was also supported by the project TG-AST080005N through TeraGrid resources provided by Texas Advanced Computing Center (<http://www.tacc.utexas.edu>).

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Multi-scale Dynamical Processes in Space and
Astrophysical Plasmas

Leubner, M.P.; Vörös, Z. (Eds.)

2012, XVI, 232 p., Hardcover

ISBN: 978-3-642-30441-5