

Cosmic Ray Acceleration in Magnetic Reconnection Sites

Elisabete M. de Gouveia Dal Pino¹, Grzegorz Kowal², and Alex Lazarian³

¹ Instituto de Astronomia, Geofísica e Ciências Atmosféricas,
Universidade de São Paulo – IAG/USP,

Rua do Matão 1226, 05508-090 São Paulo, SP, Brasil.

² Escola de Artes, Ciências e Humanidades,
Universidade de São Paulo, Rua Arlindo Bettio 1000,
CEP 03828-000, São Paulo, Brazil

³ Department of Astronomy, University of Wisconsin,
475 North Charter Street, Madison, Wisconsin 53706, USA

Cosmic Ray (CR) acceleration still challenges the researchers. Fast particles may be accelerated in astrophysical environments by a variety of processes. Acceleration in magnetic reconnection sites in particular, has lately attracted the attention of researchers not only for its potential importance in the solar system context, but also in other astrophysical environments, like compact stellar sources, AGNs and GRBs, and even in diffusive media like the ISM and the IGM, especially when the environment is magnetically dominated. In this talk we review this process and also present three-dimensional collisional MHD simulations with the injection of thousands of test particles, showing from the evolution of their energy spectrum that they can be efficiently accelerated by reconnection through a first-order Fermi process within large scale magnetic current sheets (especially when local turbulence is present making reconnection fast and the acceleration layer thicker).

CR ACCELERATION: NEW CHALLENGES

Recent years have witnessed new challenges on cosmic ray acceleration. On one side, the ultra-high-energy cosmic rays (UHECRs), which seem to be of extragalactic origin with source candidates ranging from compact stars to GRBs, AGNs or mergers of clusters of galaxies, still have their production mechanism(s) not fully understood [35]. On the other side, very high energy observations of these sources with Fermi and Swift satellites and ground based gamma ray observatories indicate that relativistic particles are being accelerated up to \sim TeV energies in very compact regions [62], possibly magnetically dominated in some cases.

The mechanisms frequently discussed in the literature for accelerating energetic particles include varying magnetic fields in compact sources, (e.g., [11, 12]), stochastic processes in turbulent environments, and acceleration behind shocks. The latter, in particular, is generally invoked as dominating in several astrophysical environments (e.g., supernova remnants) and has been extensively discussed in the literature (see the review by T. Bell in these Proceedings). An alternative, much less explored mechanism so far, involves particle acceleration within magnetic reconnection sites and in this highlight talk, we will discuss this mechanism and show that it may be also a very powerful mechanism for accelerating cosmic rays.

Magnetic Reconnection

Magnetic reconnection occurs when two magnetic fluxes of opposite polarity encounter each other (see Figure 1). In the presence of finite magnetic resistivity, the converging magnetic field lines annihilate at the discontinuity surface and a current sheet forms there. Direct observations of reconnection

indicate that at least in some circumstances, as in the solar corona and the Earth magnetotail, it is *FAST* with reconnection rates V_R of the order of the Alfvén speed v_A . However, the standard one-dimensional model of magnetic reconnection proposed separately by Sweet (1957) and Parker (1958) [57, 64], the so-called Sweet-Parker (S-P) model (Figure 1, top panel), using simple mass flux conservation arguments predicts a reconnection velocity given by $V_R \sim v_A(\Delta/L) \sim v_A S^{-1/2} \ll 1$, where $S = Lv_A/\eta$ is the Landquist number, with L being the large scale extension of the reconnection layer, Δ the thickness of the reconnection contact discontinuity, $v_A = B/(4\pi\rho)^{1/2}$ the Alfvén speed, B the reconnecting magnetic field, ρ the local density, and η the Ohmic resistivity which is generally very small in the typically high-conducting astrophysical plasmas, resulting very large Landquist numbers. Thus, in contrast to the observations above, the S-P model predicts a slow reconnection regime.

Petschek (1964) [58] proposed a way to solve this difficulty by assuming a two-dimensional geometry and making $\Delta \sim L$ by focussing the reconnection process into a single point, the X-point, rather than over the entire large scale L of the magnetic fluxes (see Figure 1, middle panel). Such a configuration indeed results a fast reconnection speed $V_R \sim \pi/4(v_A \ln S)$. However, it was later found to be unstable, rapidly collapsing to the S-P configuration in magnetohydrodynamical (MHD) numerical simulations [6], unless a collisionless pair plasma with localized resistivity η is considered [5, 69]. In a collisionless two-fluid plasma, the particles' mean free path is of the order of the large scale dimension of the system ($L \sim \lambda_{mfp}$). Under such conditions, in an electron-ion plasma, for instance, the ion skin depth δ_{ion} (which can be viewed as the gyroradius of an ion moving at the Alfvén speed, i.e. $\delta_{ion} = v_A/\omega_{ci}$, where ω_{ci} is the ion cyclotron frequency) is comparable to the S-P diffusion scale ($\Delta_{SP} = (L\eta/v_A)^{1/2}$). (In the case of an electron-positron pair plasma, a similar condition is

valid for the electron skin depth.) But at these scales, the Hall effect given by the $\vec{J} \times \vec{B}$ term in Ohm's law is important and able to sustain the Petschek-X-point configuration. In a collisional plasma, on the other hand, the S-P thickness is larger than the microphysical length scales relevant to collisionless reconnection, i.e., $\delta_{ion} \ll \Delta_{SP}$ or $L \gg \lambda_{e,mfp} (m_i/m_e)^{1/2}$ and the Hall effect is no longer dominant [59, 60, 68].

From the analysis above one could reach the conclusion that fast reconnection would be possible only in collisionless plasmas. Fortunately, this is not true and the reason is because nature provides an ubiquitous process that is turbulence and this makes reconnection fast in collisional MHD fluids. This process was first described by Lazarian & Vishniac (1999) [41] and successfully tested with numerical simulations [36, 38]. In a turbulent medium, the wandering of the magnetic field lines allows for many simultaneous events of reconnection which make it fast (Figure 1, bottom panel). Indeed, one can demonstrate that $V_R \sim v_A (l/L)^{1/2} (v_l/v_A)^2$, where v_l is the injection velocity of the turbulence and l its injection scale. It is easy to see that for $l \sim L$ and $v_l \sim v_A$, $V_R \sim v_A$ and therefore, reconnection is fast! Besides, we see that the presence of turbulence makes the reconnection layer thicker ($\Delta \sim l \sim L$) and intrinsically three-dimensional. Both features will be very important for accelerating particles, as will see in Section 3. Later similar descriptions of fast reconnection in collisional MHD were also proposed by other authors ([47, 61]; see also [66] for a review).

MAGNETIC RECONNECTION AND FIRST-ORDER FERMI COSMIC RAY ACCELERATION

Fast reconnection breaks the magnetic field topology, releases magnetic energy into the plasma in short time and is able to explain the bursty emission of, e.g., solar/stellar flares. In the later case, relativistic particle acceleration is always observed in connection with the flares. Thus the obvious question that one may pose is: can magnetic reconnection lead to direct efficient particle acceleration? In the next paragraphs, we will discuss this issue.

Traditionally, particle acceleration in a reconnection site is thought as due to the advective electric field created within the current sheet along the z -axis (see top-left diagram in Figure 2). This reconnection electric field actually allows for a linear acceleration along the z direction and is given by $\varepsilon_z = V_R B/c$ [63].

In analogy to the shock acceleration mechanism where particles confined between the upstream (unshocked) and downstream (shocked) flows undergo a first-order Fermi acceleration (with a net energy increase after moving back and forth $\langle \Delta E/E \rangle \sim v/c$, [4, 26]), de Gouveia Dal Pino & Lazarian, in 2005 [13] (henceforth GL05) proposed that a similar mechanism would occur when particles are trapped between the two converging flux tubes moving to each other with V_R in a magnetic reconnection current sheet (Figure 2). They showed that, as particles bounce back and forth due to head-on collisions

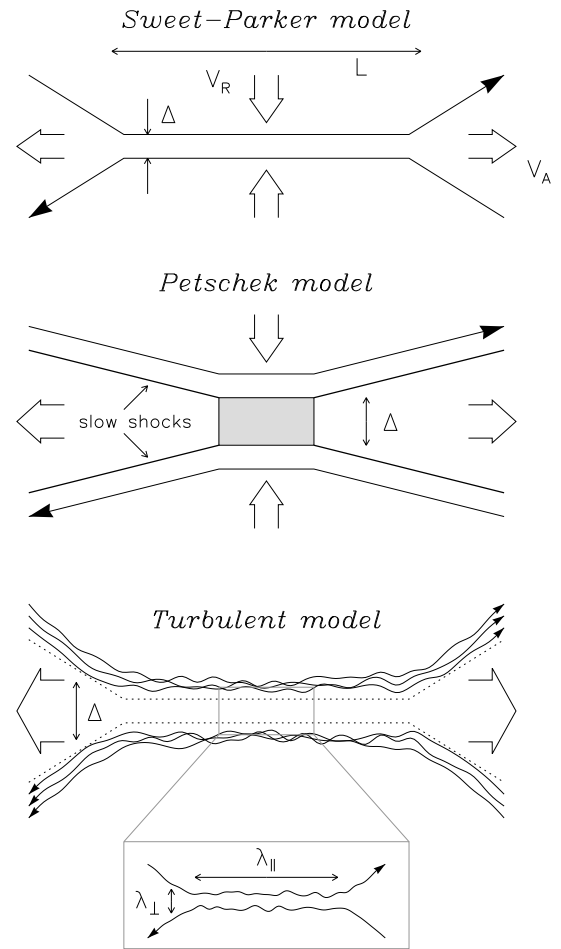


FIG. 1. Schematic configurations of three different magnetic reconnection models. Top: Sweet-Parker model; middle: Petschek model; and bottom: turbulent reconnection model.

with magnetic fluctuations in the current sheet, their energy after a round trip increases by $\langle \Delta E/E \rangle \sim 8V_R/3c$, which implies a first-order Fermi process with an exponential energy growth after several round trips (see also [17, 46]). (Interestingly, Giannios (2010, [27]) assuming relativistic reconnection, obtained an energy increase $\langle \Delta E/E \rangle \sim 4\beta_R/3 + \beta_R^2/2$, where $\beta = V_R/c$, which in the limit that $\beta_R \ll 1$ recovers the expression obtained by GL05 for non relativistic reconnection.)

As remarked earlier, under fast magnetic reconnection conditions, e.g., induced by turbulence [41], V_R can be of the order of the local Alfvén speed V_A . In particular, at the surroundings of relativistic sources $V_R \simeq v_A \simeq c$ and thus the mechanism can be rather efficient [13, 14, 27, 43]. GL05 [13] have also derived analytically a power-law energy distribution for the accelerated particles ($N(E) \sim E^{-5/2}$) and a corresponding electron synchrotron radio power-law spectrum which is compatible with, e.g., the observed radio flares from galactic black hole binary systems (or microquasars).

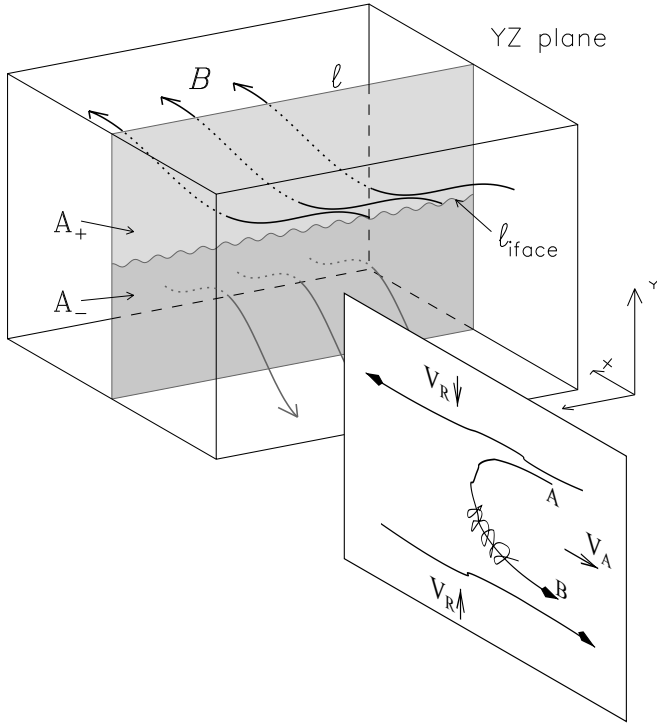


FIG. 2. *Top left: three-dimensional view of a magnetic reconnection sheet. Bottom right: detail of a particle being accelerated within the reconnection site. It spirals about a reconnected magnetic field line and bounces back and forth between points A and B. The reconnected regions move towards each other with the reconnection velocity V_R . Particles gain energy due to "collisions" with the magnetic irregularities within the two converging fluxes like in the first-order Fermi process in shock fronts (see GL05 [13]). Adapted from [36, 46].*

If one relaxes the assumption considered in the derivation by GL05 that the particles escape from the acceleration zone with a similar rate as in shock acceleration, one obtains [25] a particle energy spectrum $N(E) \sim E^{-(r+2)/(r-1)}$, where $r = \rho_2/\rho_1$, and ρ_1 and ρ_2 are the densities in the inflow and outflow regions of the reconnection site, respectively. Surprisingly, this gives the same power-law index as in shocks and, when the compression ratio r is large, $N(E) \sim E^{-1}$. We note however, that in the case of fast reconnection induced by turbulence [41], reconnection does not depend on the compression ratio. On the other hand, one needs to keep high anisotropy between the parallel and perpendicular components of the accelerated particle velocities in order to ensure efficient particle acceleration (see [17, 46] and simulations below).

The considerations above also allow one to estimate the acceleration time-scale due to reconnection. The simplest way to evaluate this is by setting the energy of the accelerated particle E equal to $e(V_R/c)Bz$, where z is the distance travelled by the particle in the current sheet (normal to the large scale magnetic field direction) while being accelerated by the effective electric field $(V_R/c)B$. This gives (e.g. [27, 63]) $t_{\text{acc}} \simeq z/c \simeq \frac{E}{eV_R B}$.

Similarly, a simple way to estimate the maximum energy that a particle can reach is by realizing that it can no longer be confined within the reconnection region when its Larmor radius becomes larger than the thickness of the reconnection layer ℓ_{rec} . This implies that $E_{\text{max}} \simeq e c \ell_{\text{rec}} B$.

IS MAGNETIC RECONNECTION REALLY A POWERFUL PROCESS TO ACCELERATE PARTICLES?

A way to probe the analytical results above is through numerical simulations. So far, most of the numerical studies of particle acceleration by magnetic reconnection have been performed for two-dimensional (2D) collisionless positron-electron plasmas by means of particle-in-cell (PIC) simulations (e.g., [21, 24, 72]). However, these apply to kinetic scales of only a few hundred plasma inertial lengths ($\sim 100c/\omega_p$, where ω_p is the plasma frequency). The generally much larger scales of the astrophysical systems (e.g., pulsars, AGNs, GRBs, etc) frequently require a collisional MHD description of reconnection.

Recent studies in this direction undertaken by [15, 16, 37, 38, 46] modelled different domains of magnetic reconnection in two (2D) and three-dimensions (3D) solving the isothermal MHD equations numerically in a Godunov-type scheme. 10,000 test particles were injected in these MHD domains with random initial positions and directions and with an initial thermal energy distribution. For each particle the relativistic equation of motion is solved

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

where m , q and \vec{u} are the particle mass, electric charge and velocity, respectively, \vec{E} and \vec{B} are the electric and magnetic fields, respectively, $\gamma \equiv (1 - u^2/c^2)^{-1/2}$ is the Lorentz factor, and c is the speed of light. The effective electric field \vec{E} is taken from the MHD simulations, $\vec{E} = -\vec{v} \times \vec{B} + \eta \vec{J}$, where \vec{v} is the plasma velocity, $\vec{J} \equiv \nabla \times \vec{B}$ is the current density, and η is the Ohmic resistivity coefficient. We note that the effect of the latter resistive term on particle acceleration is negligible [37].

Figure 3 zooms in the details of the acceleration of a single test particle within a resistive Sweet-Parker shaped current sheet [37]. Before the particle reaches the current sheet discontinuity it is drifted by the plasma inflow and the increasing gradient of B . When it enters the discontinuity (the white part of the trajectory in the upper panel), it bounces back and forth several times and gains energy (which increases exponentially as shown in the detail of the lower panel of the Figure) due to head-on collisions with magnetic irregularities in the shrinking flow, on both sides of the magnetic discontinuity, in a first order Fermi process, as described in GL05 [13]. At the same time it drifts along the magnetic lines which eventually allow it to escape from the acceleration region.

Figure 4 presents an evolved 2D MHD configuration with eight Harris current sheets in a periodic box also computed

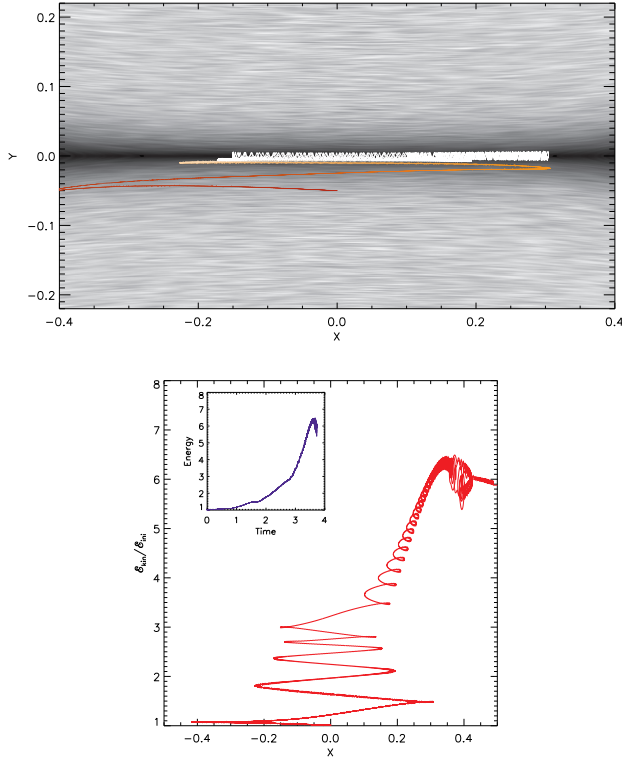


FIG. 3. Numerical test of first-order Fermi acceleration within a current sheet with a Sweet-Parker configuration. The top panel shows the trajectory of a test proton approaching the discontinuity layer and bouncing back and forth several times. The color of the trajectory corresponds to the particle energy (which increases from red to yellow and then finally to white when the particle reaches the current sheet). The bottom panel shows the evolution of the particle energy which increases exponentially when the particle reaches the current sheet. In the model of Sweet-Parker reconnection presented in this figure we used explicit large resistivity coefficient $\eta = 10^{-3}$ in order to make reconnection fast. The grid size in the model was set to $\Delta x = 1/1024$. From [37].

by [37]. Random weak velocity fluctuations were imposed to this environment in order to enable spontaneous reconnection and the development of 2D magnetic islands. The merging of magnetic islands and the resulting stretching or shrinking in some locations is evident. The authors [37] find that within the contracting magnetic islands and the current sheets the injected 10,000 test particles accelerate predominantly through the first order Fermi process, as previously described, while outside of the current sheets and islands the particles experience mostly drift acceleration due to magnetic fields gradient. Their energy increases exponentially due to the Fermi process and the spectrum of the accelerated particles develops a high energy power law tail. Similar results were found in 2D collisionless pair plasma PIC simulations [9, 21, 23, 24, 72].

The results above confirm that the first-order Fermi acceleration process within shrinking islands is not restricted to collisionless physics or kinetic effects as previously suggested

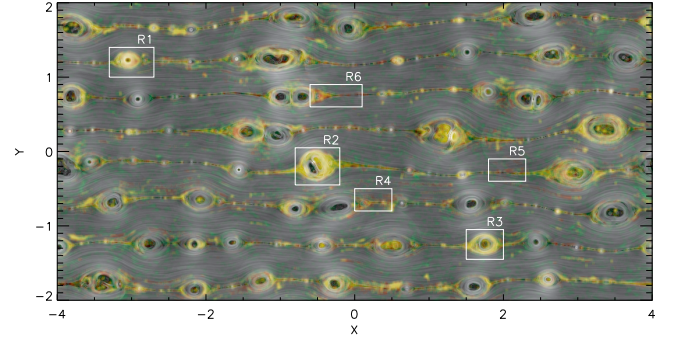


FIG. 4. 2D MHD configuration with eight current sheets and 10,000 test particles. The topology of the magnetic field is represented as a gray texture with semi-transparent color maps representing locations where the parallel and perpendicular particle velocity components are accelerated. There is no guide field ($B_z = 0.0$). The red and green colors correspond to regions where either parallel or perpendicular acceleration occurs, respectively, while the yellow color shows locations where both types of acceleration occur. The parallel component increases in the contracting islands and in the current sheets, while the perpendicular component increases mostly in the regions between current sheets. White boxes show regions that have been more carefully analysed in [37]. The simulation was performed with the resolution 8192×4096 . The particles were injected with an initial thermal distribution with a temperature corresponding to the sound speed of the MHD model (from [37].)

(e.g. [21, 23, 24] and references therein). This acceleration mechanism in reconnection sites works also in collisional plasmas, under the MHD approximation, as shown above and, in fact, MHD codes present a way to study the physics of particle acceleration numerically at large scales. Acceleration in reconnection regions is thus a universal process which is not constrained by the details of the plasma physics and can be also very efficient in collisional gas.

These authors [37] have also investigated particle acceleration in 3D MHD domains of reconnection and shown that its behaviour is quite distinct from the acceleration in 2D domains. In three-dimensions, the 2D magnetic islands break into loops and the parallel component of the particle velocities keeps accelerating in opened loops along the out-of-plane (z) direction. Acceleration in 3D reconnection is more like 2D reconnection with a mild guide field normal to the multiple current-sheet plane. In this case, as in 3D, the acceleration is not constrained to occur within merging islands in the plane only, but occurs also in open loops along the guide field [37]. However, if the guide field becomes too strong, then this will decrease the merge of islands and inhibit the overall acceleration process. This has been also found in studies of particle acceleration in collisionless flows (e.g., [9, 72]).

In the previous examples of particle acceleration in collisional MHD, reconnection was made fast by means of enhanced numerical resistivity. But, as remarked, reconnection can be made naturally fast when considering the universal presence of turbulence [41]. Figure 5 shows a 3D MHD numerical simulation where [38] introduced turbulence within a

current sheet with a Sweet-Parker configuration and followed the trajectories of 10,000 protons injected in this domain. As we see, an important consequence of the presence of turbulent magnetic fields is the formation of a thick volume filled with small scale magnetic fluctuations. This ensures a more efficient acceleration than in the Sweet-Parker configuration since the size of the acceleration zone and the number of scatterers is larger. Figure 5 also depicts the evolution of the kinetic energy of the particles. Particles are continually accelerated by encounters with several small and intermediate scale current sheets randomly distributed in the thick shrinking volume and the acceleration process is clearly a first-order Fermi process, as in the previous cases. We note that, after reaching the energy level $\sim 10^4$, the particles accelerate at smaller rates, this is because their Larmor radii at this energy becomes comparable to the thickness of the acceleration region, and this is consistent with the maximum predicted energy evaluated in Section 2 for first-order Fermi acceleration. Further energy increase beyond this value is due to a much slower drift acceleration (of the perpendicular component only) caused by the large scale magnetic fields gradients.

An inspection of the particle spectrum in the subplot of the bottom panel of Figure 5 at $t=5$ c.u. reveals already the formation of a hard power law spectrum $N(E) \sim E^{-1}$ in the energy range $E/m_p c^2 \sim 10 - 10^3$, where m_p is the proton mass. This power law index is compatible with former results obtained from 2D collisionless PIC simulations considering merging islands [24], or X-type Petschek's configurations (e.g., [72]).

Also from the simulations we can derive the acceleration time. Preliminary results from a number of collisional MHD numerical simulations with injection Alfvén velocities in the range $v_A/c \sim 1/1000 - 1/5$ [19, 37, 38], indicate that the acceleration time is nearly independent of the initial Alfvén (and reconnection) speed) and $t_{acc} \sim E^{0.4}$. This is generally longer than the estimated time in Section 2, but becomes comparable to it as one approaches the maximum energy that the particles can reach in the acceleration zone [19].

It should be remarked that the collisional MHD simulations shown here focussed on proton acceleration. Although applicable to electrons too, the numerical integration of the electron trajectories is much longer. Nevertheless, such tests are also needed.

Those authors [38] have also tested the acceleration of particles in *pure* MHD turbulence, where particles suffer collisions both with approaching and receding magnetic irregularities. The acceleration rate is smaller in this case and suggests that the dominant process is a second-order Fermi. We note that other recent studies have also explored test particle acceleration both in turbulent and in resistive MHD domains (see [20, 28, 29, 56]), but did not explore the nature of the mechanism accelerating the particles.

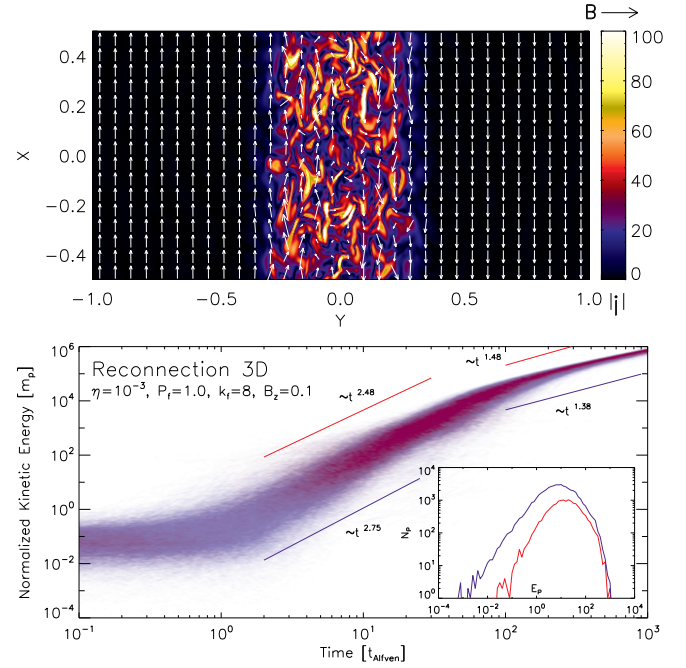


FIG. 5. *Bottom panel:* particle kinetic energy distributions for 10,000 protons injected in a 3D current sheet with turbulence which makes reconnection fast. The colors indicate which velocity component is accelerated (red or blue for parallel or perpendicular, respectively). The energy is normalized by the rest proton energy. The subplot shows the particle energy distributions at $t = 5.0$. *Top panel:* XY cuts through the domain at $Z = 0$ of the absolute value of current density $|\vec{J}|$ overlapped with the magnetic vectors. It was employed $B_{0z} = 0.1$, $\eta = 10^{-3}$, and a resolution $256 \times 512 \times 256$ (from [38]).

PARTICLE ACCELERATION IN RELATIVISTIC RECONNECTION SITES

In this review, we discussed mostly Fermi acceleration considering non-relativistic reconnection environments, that is, generally assuming V_R smaller than the light speed. However, in systems like, e.g. the surroundings of black holes and pulsars, $v_A \sim c$ and then, since in fast reconnection V_R must approach v_A , reconnection itself may become relativistic in such domains. There has been some advancement in relativistic reconnection studies too. The theoretical grounds have been established by a number of authors ([7, 10, 30, 31, 34, 48–50, 52, 73, 74]; see also [17, 66] and references therein for reviews). Essentially, it has been found that Sweet-Parker reconnection in the relativistic regime is slow, as in the non-relativistic regime, while 2D X-point Petschek's reconnection predicts a fast rate as in the non-relativistic regime [50]. The numerical advances in relativistic reconnection have been performed so far only for 2D collisionless X-point Petschek's configurations by means of PIC simulations of pair plasmas, and have confirmed the results of the analytical theory. In such relativistic collisionless electron-positron pair plasmas, the investigation of relativistic particle acceleration is

almost straightforward. Studies e.g., by [72] have revealed results which are compatible with those of acceleration in non-relativistic reconnection.

However, studies of particle acceleration in the collisional relativistic MHD regime (RMHD) are still in their childhood. Preliminary results of numerical simulations of *in situ* particle acceleration in relativistic jets (see Figure 8 of [17]) indicate that both, shock acceleration and acceleration by magnetic reconnection are competitive mechanisms.

These results are encouraging and may have rather important consequences on particle acceleration and high energy emission processes in compact sources (see below).

A FEW APPLICATIONS

As remarked, magnetic reconnection is very frequent and therefore, it should be expected to induce acceleration of particles in a wide range of galactic and extragalactic environments. Originally discussed predominantly in the context of solar flares [21, 22, 28, 29, 71] and earth magnetotail [23, 44, 45], it has been gaining importance beyond the solar system, in more extreme astrophysical environments and sources, such as in the production of ultra high energy cosmic rays [27, 35], in particle acceleration in jet-accretion disk systems [13–15, 18, 27], and in the general framework of compact sources, as AGNs and GRBs [15, 16, 27, 42, 66, 70, 72, 74], and even in pulsar nebulae, like Crab [9].

For instance, assuming multiple magnetic field reversals along the jet as in Figure 3 (imprinted at the jet launching region near the light cylinder), [27] estimated that AGN and GRB jets would be able to produce UHECRs through first-order Fermi acceleration by magnetic reconnection (GL05, [13]). The multiple reversals can easily produce a power law spectrum of relativistic particles, as we have seen, e.g. in [37], but this model still requires numerical testing using specific conditions of relativistic jets in order to see whether such high energies can be really achieved.

Another potential site for particle acceleration by reconnection has been explored by [13–15, 32] at the corona of accretion disks around compact sources (like AGNs and galactic BHs). They computed the magnetic power arising from fast reconnection in the inner disk region and found a correlation with the mass of the sources over 10^9 orders of magnitude in mass. Plotting in the same diagram the Synchrotron radio power observed for more than 100 galactic BHs and different classes of AGNs, they found that the predicted magnetic reconnection power is more than sufficient to explain particle acceleration and the observed radio and gamma outbursts from both galactic BHs and low luminous AGNs, but not those from high luminous AGNs. This result might offer a physical interpretation for the so called *Fundamental Plane* [53] which correlates the emission of galactic BHs and low luminous AGNs. They also concluded that the lack of correlation with high luminous AGNs (e.g., BL Lacs for which the jet is oriented towards the line of sight) is due to the fact that in such

cases the nuclear emission is screened by the high density and radiation fields around the nucleus and what is observed is the emission from the jet further out in such cases. This result is also compatible with recent findings of [55] (see also [32]).

Another example explores the potential effects of acceleration by reconnection in the Crab nebula. Puzzling Synchrotron flares with energy larger than the classical ideal MHD limit $E > E_{max} \sim 9mc^2/4sF \sim 160$ MeV have been observed in this source and attributed to randomly oriented relativistic mini-jets driven by reconnection (see [8]). These authors evaluated the acceleration of the particles due to reconnection in such mini-jets and concluded that this would be able to reproduce the observed spectral energy distribution. It is interesting that this model presents features which resemble the fast reconnection model of acceleration mediated by turbulence as in Figure 4.

FORTHCOMING STUDIES

Cosmic ray acceleration investigation in magnetic reconnection sites is still in its youth, particularly in collisional MHD and relativistic regimes. Current studies in this regard include relativistic MHD fast reconnection involving turbulence (e.g. [17]) and relativistic reconnection of electron-ion, high energy density, radiative plasmas (e.g. [?]). These are fundamental issues specially for modelling flares and variability in the spectrum of compact sources, like AGNs, GRBs, microquasars, etc.

Also, particle acceleration in diffuse domains of reconnection, particularly in pure turbulent regions like the ISM and IGM, deserves attention as these particles may be available, e.g., as seed populations for further acceleration in shocks or magnetic reconnection regions in embedded sources.

Forthcoming studies will also require the inclusion of the relevant loss mechanisms of the accelerated particles, in order to assess the importance of the acceleration by reconnection in comparison to other processes (e.g., shock acceleration) and to reproduce the observed spectra and light curves of the sources (see e.g., [9, 33]).

In conclusion, magnetic reconnection is now recognized as an essential process not only in the solar system, but also beyond it, in a large number of astrophysical sources, including turbulent environments which in turn, are ubiquitous. In this situation the acceleration of cosmic rays by reconnection may play a vital role and deserves extensive investigation, specially to help in the interpretation of current high energy observations and in making predictions for upcoming new generation of instruments, like the Cherenkov Telescope Array ([1–3, 62]).

Acknowledgements

E.M.G.D.P. acknowledges partial support from the Brazilian agencies FAPESP (grant no. 2006/50654-3 and CNPq

(grant no. 300083/94-7) and G.K. also acknowledges support from FAPESP (grant 2009/50053-8). Part of the simulations presented here have been carried out in LAI (Astrophysical Laboratory of Informatics at IAG-USP).

-
- [1] Actis, M. et al. (CTA collaboration) 2011, *Exp. Astron.*, 32, 193
 - [2] Acharya, B.S. et al. (CTA collaboratioN) 2013, *Astropart. Phys.*, 43, 3 (2013)
 - [3] Barres de Almeida, U. & de Gouveia Dal Pino, E. M. 2013, *BJP* (special issue for 2012 Texas Symp.) (in press)
 - [4] Bell, A. R. 1978, *Mon. Not. R. Astron. Soc.*, 182, 147
 - [5] Birn, J., Drake, J.F., Shay, M.A., Rogers, B.N., Denton, R.E., Hesse, M., Kuznetsova, M., Ma, Z.W., Bhattacharjee, A., Otto, A. & Pritchett, P.L., 2001, *J. Geophys. Res.* 106, 3715
 - [6] Biskamp, D. 1996, *Astrophysical Space Science*, 242, 165
 - [7] Blackman, E.G. & Field, G.B. 1994, *Physical Review Letters* 72, 494
 - [8] Clausen-Brown, E., & Lyutikov, M. 2012, *Mon. Not. R. Astron. Soc.*, 426, 1374
 - [9] Cerutti, B., Werner, G. R., Uzdensky, D. A., & Begelman, M. C. 2013, *The Astrophysical Journal*, 770, 147
 - [10] Coroniti, F.V. 1990, *Astrophys. J.* 349, 538
 - [11] de Gouveia Dal Pino, E. M. & Lazarian, A. 2000, *The Astrophysical Journal Letters*, 536, L31
 - [12] de Gouveia Dal Pino, E. M. & Lazarian, A. 2001, *The Astrophysical Journal*, 560, 358
 - [13] de Gouveia Dal Pino, E. M. & Lazarian, A. 2005, *Astronomy and Astrophysics*, 441, 845
 - [14] de Gouveia Dal Pino, E. M., Piovezan, P. P. & Kadowaki, L. H. S. 2010a, *Astronomy and Astrophysics*, 518, A5
 - [15] de Gouveia Dal Pino, E. M., Kowal, G., Kadowaki, L. H. S., Piovezan, P., & Lazarian, A. 2010b, *International Journal of Modern Physics D*, 19, 729
 - [16] de Gouveia Dal Pino, E. M., Kowal, G., Lazarian, A., & Santos-Lima, R. 2011, *arXiv: 1107.26742*
 - [17] de Gouveia Dal Pino, E. M. and Kowal, G. 2013, in *Magnetic Fields in Diffuse Media*, *arXiv:1302.4374*
 - [18] del Valle, M. V., Romero, G. E., Luque-Escamilla, P. L., Martí, J., & Ramón Sánchez-Sutil, J. 2011, *The Astrophysical Journal*, 738, 115
 - [19] del Valle, M. V., de Gouveia Dal Pino, E. M., Kowal, G., & Romero, G. E., 2013 (in prep.)
 - [20] Dmitruk, P., Matthaeus, W. H., Seenu, N., & Brown, M. R. 2003, *Astrophysical Journal Letters*, 597, L81
 - [21] Drake, J. F., Swisdak, M., Schoeffler, K. M., Rogers, B. N., & Kobayashi, S. 2006, *Geophys. Res. Lett.*, 33, 13105
 - [22] Drake, J. F., Cassak, P. A., Shay, M. A., Swisdak, M., & Quataert, E. 2009, *Astrophys. J. Lett.*, 700, L16
 - [23] Drake, J. F., Opher, M., Swisdak, M., & Chamoun, J. N. 2010, *The Astrophysical Journal*, 709, 963
 - [24] Drake, J. F., Swisdak, M., & Fermo, R. 2012 (submitted)
 - [25] Drury, L. O. 2012, *Mon. Not. R. Astron. Soc.*, 422, 2474
 - [26] Fermi, E. 1949, *Physical Review*, 75, 1169
 - [27] Giannios, D. 2010, *Mon. Not. R. Astron. Soc.*, 408, L46
 - [28] Gordovskyy, M., Browning, P. K., & Vekstein, G. E. 2010, *The Astrophysical Journal*, 720, 1603
 - [29] Gordovskyy, M. & Browning, P. K. 2011, *The Astrophysical Journal*, 729, 101
 - [30] Hesse, M. & Zenitani, S. 2007, *Physics of Plasmas* 14 (11), 112102
 - [31] Jaroschek, C.H., Treumann, R.A., Lesch, H., Scholer, M. 2004, *Physics of Plasmas* 11, 1151
 - [32] Kadowaki, L. & de Gouveia Dal Pino, E. M. 2013 (in prep.)
 - [33] Khiali, B., de Gouveia Dal Pino, E. M., Kowal, G., del Valle, M. V., Sol, H. 2013 (in prep.)
 - [34] Komissarov, S.S. 2007, *Mon. Not. Roy. Astron. Soc.* 382, 995
 - [35] Kotera, K. & Olinto, A. V. 2011, *Annu. Rev. Astron. Astrophys.*, 49, 119
 - [36] Kowal, G., Lazarian, A., Vishniac, E. T., & Otmianowska-Mazur, K. 2009, *The Astrophysical Journal*, 700, 63
 - [37] Kowal, G., de Gouveia Dal Pino, E. M., & Lazarian, A. 2011, *The Astrophysical Journal*, 735, 102
 - [38] Kowal, G., de Gouveia Dal Pino, E. M., & Lazarian, A. 2012, *Physical Review Letters*, 108, 241102
 - [39] Kowal, G., de Gouveia Dal Pino, E. M., & Lazarian, A. 2013 (in prep.)
 - [40] Kowal, G., Lazarian, A., Vishniac, E. T., & Otmianowska-Mazur, K. 2012, *The Astrophysical Journal*, in press
 - [41] Lazarian, A. & Vishniac, E. T. 1999, *The Astrophysical Journal*, 517, 700
 - [42] Lazarian, A., Petrosian, V., Yan, H. & Cho, J. 2003, Review at the NBSI workshop "Beaming and Jets in Gamma Ray Bursts", Copenhagen, August 12-30, 2002 (*arXiv:astro-ph/0301181*)
 - [43] Lazarian, A. 2005, in *AIP Conf. Proc. Ser. 784, Magnetic Fields in the Universe: From Laboratory and Stars to Primordial Structures*, ed. E. M. de Gouveia dal Pino, G. Lugones, & A. Lazarian (Melville, NY:AIP), 42
 - [44] Lazarian, A. & Opher, M. 2009, *The Astrophysical Journal*, 703, 8
 - [45] Lazarian, A. & Desiati, P. 2010, *The Astrophysical Journal*, 722, 188
 - [46] Lazarian, A., Kowal, G., Vishniac, E., & de Gouveia Dal Pino, E. 2011, *Planetary and Space Science*, 59, 537
 - [47] Loureiro, N. F., Schekochihin, A. A., & Cowley, S. C. 2007, *Physics of Plasmas*, 14, 100703
 - [48] Romanova, M.M. & Lovelace, R.V.E. 1992, *Astron. Astrophys.* 262, 26
 - [49] Lyubarsky, Y. & Kirk, J.G. 2001, *Astrophys. J.* 547, 437
 - [50] Lyubarsky, Y.E. 2005, *Mon. Not. Roy. Astron. Soc.* 358, 113
 - [51] Lyubarsky, Y. & Liverts, M. 2008, *The Astrophysical Journal*, 682, 1436
 - [52] Lyutikov, M. 2003, *Mon. Not. Roy. Astron. Soc.* 346, 540
 - [53] Merloni, A., Heinz, S., & di Matteo, T. 2003, *Mon. Not. R. Astron. Soc.*, 345, 1057
 - [54] Mignone, A. 2007, *Journal of Computational Physics*, 225, 1427
 - [55] Nemmen, R. S., Georganopoulos, M., Guiriec, S., et al. 2012, *Science*, 338, 1445
 - [56] Onofri, M., Isliker, H., & Vlahos, L. 2006, *Physical Review Letters*, 96, 151102
 - [57] Parker, E. N. 1957, *J. Geophys. Res.*, 62, 509
 - [58] Petschek, H.E, 1964, *Magnetic Field Annihilation*, in *The Physics of Solar Flares*, ed. by W.N. Hess, p. 425
 - [59] Shay, M. A., Drake, J. F., Denton, R. E., & Biskamp, D. 1998, *J. Geophys. Res.*, 103, 9165
 - [60] Shay, M. A., Drake, J. F., & Swisdak, M. M. 2004, *Physics of Plasmas*, 11, 2199
 - [61] Shibata, K., & Tanuma, S. 2001, *Earth, Planets, and Space*, 53, 473
 - [62] Sol, H., Zech, A., Boisson, C. et al. 2013, *Astroparticle Physics*, 43, 215
 - [63] Speiser, T. W., 1965, *J. Geophysical Res.*, 70, 4219

- [64] Sweet, P. A. 1958, Conf. Proc. IAU Symposium 6, *Electromagnetic Phenomena in Cosmical Physics*, ed. B. Lehnert, (Cambridge, UK:Cambridge University Press), 123
- [65] Uzdensky, D. A. 2010,
- [66] Uzdensky, D. A. 2011, Space Sc. Rev., 101
- [67] Uzdensky, D. A. & McKinney, J. C. 2011, Phys. Plas., 18, 042105
- [68] Yamada, M., Ren, Y., Ji, H., Breslau, J., Gerhardt, S., Kulsrud, R., & Kurisyn, A. 2006, Phys. of Plasmas, 13, 0521229
- [69] Yamada, M., Kulsrud, R. & Ji, H. 2010, Reviews of Modern Physics 82 , 603
- [70] Zhang, B. & Yan, H. 2011, The Astrophysical Journal, 726, 90
- [71] Zharkova, V. V. & Siversky, T. 2011, in AIP Conf. Proc. Ser., Advances in Plasma Astrophysics: IAU 274th Meeting, ed. A. Bonanno, E. M. de Gouveia Dal Pino, & A. Kosovichev (Cambridge University Press, NY:AIP)
- [72] Zenitani, S. & Hoshino, M. 2001, The Astrophysical Journal, 562, L63
- [73] Zenitani, S. & Hoshino, M. 2008 Astrophys. J. 677, 530
- [74] Zenitani, S., Hesse, M. & Klimas, A. 2009, Astrophys. J. 696, 1385