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Cosmic Ray Acceleration via Turbulence-Induced Magnetic Reconnection: From Micro to Macro Scales

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Abstract

Turbulence-driven magnetic reconnection is increasingly recognized as a crucial mechanism for accelerating cosmic rays (CRs) to ultra-high energies (UHEs) in magnetized astrophysical environments, ranging from compact sources to more extended regions. In this contribution, we provide an overview of this acceleration process and present a comparative analysis of 3D magnetohydrodynamic (MHD) and particle-in-cell (PIC) simulation results.
We explore how cosmic ray acceleration unfolds across both microscopic and macroscopic scales, drawing insights from 3D PIC kinetic simulations, hybrid 3D MHD-PIC models, and large-scale 3D MHD simulations. While micro-scale simulations are essential for understanding the initial stages of particle acceleration—commonly referred to as the injection problem—macro-scale MHD models help determine the maximum energies particles can reach. We briefly summarize the key similarities and differences between these regimes, their influence on acceleration rates and spectral properties, and the transition from microscopic to macroscopic scales.
Furthermore, we examine how 3D turbulence-driven reconnection efficiently CRs to high energies primarily in a Fermi process and its implications for astrophysical sources, particularly AGN accretion disks and jets. This mechanism offers a compelling explanation for the observed gamma-ray and neutrino emissions from magnetized regions, in sources such as TXS 0506+056, Mrk 501, and NGC1068.

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Cosmic Ray Acceleration via Turbulence-Induced Magnetic Reconnection: From Micro to Macro Scales

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Turbulence-driven magnetic reconnection is increasingly recognized as a crucial mechanism for accelerating cosmic rays (CRs) to ultra-high energies (UHEs) in magnetized astrophysical environments, ranging from compact sources to more extended regions. In this contribution, we provide an overview of this acceleration process and present a comparative analysis of 3D magnetohydrodynamic (MHD) and particle-in-cell (PIC) simulation results. We explore how cosmic ray acceleration unfolds across both microscopic and macroscopic scales, drawing insights from 3D PIC kinetic simulations, hybrid 3D MHD-PIC models, and large-scale 3D MHD simulations. While micro-scale simulations are essential for understanding the initial stages of particle acceleration—commonly referred to as the injection problem—macro-scale MHD models help determine the maximum energies particles can reach. We briefly summarize the key similarities and differences between these regimes, their influence on acceleration rates and spectral properties, and the transition from microscopic to macroscopic scales. Furthermore, we examine how 3D turbulence-driven reconnection efficiently CRs to high energies primarily in a Fermi process and its implications for astrophysical sources, particularly AGN accretion disks and jets. This mechanism offers a compelling explanation for the observed gamma-ray and neutrino emissions from magnetized regions, in sources such as TXS 0506+056, Mrk 501, and NGC1068.

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1. Introduction

Recent progress in high-energy astrophysics evidences the central role of magnetic reconnection in accelerating particles and producing very-high-energy (VHE) flares in magnetically dominated zones of compact systems—accretion flows, relativistic jets, pulsar-wind nebulae, and gamma-ray bursts [e.g., 1–8].

Particle acceleration by reconnection has been explored on two complementary fronts: kinetic (micro) scales, mainly via 2D PIC simulations [e.g., 4, 7, 9–14], and macroscopic (astrophysical) scales, primarily with 3D MHD simulations [e.g., 8, 15–21] A concise comparison is given in [22]; key points are summarized below.

PIC regime (micro): simulations typically span $\sim 10^2$ to few 10^3 inertial lengths (c/ω_p), i.e., regions many orders of magnitude smaller than astrophysical sources (e.g., $\sim 10^{-17}$ of an AGN jet's size). Fast reconnection is generally triggered by tearing-mode instabilities, forming 2D plasmoids (magnetic islands) and yielding limited energy gains: particles reach at most a few $10^3\, mc^2$, which are then extrapolated to larger scales. The dominant accelerating field is resistive, tied to the current density.

MHD regime (macro): 3D MHD with test particles targets source-sized environments, where fast reconnection arises primarily from turbulence and the associated breakdown of flux freezing [23–26]. Such turbulence can be driven by magneto-rotational instability (MRI) or Parker-Rayleigh-Taylor in corona/disks [e.g. 27], or by Kelvin–Helmholtz (K-H) and current driven kink (CDK) instabilities in jets [e.g., 8, 21, 28, 29]. In this setting, CRs are able to achieve ultra-high energies predominantly via first-order Fermi cycles in 3D reconnecting flux tubes across the turbulent cascade that underlies large scale magnetic fields [8, 16, 17, 19, 21, 29]. The relevant electric field is non-resistive, arising from the ($\mathbf{v} \times \mathbf{B}$) term associated with turbulent fluctuations feeding the reconnection layers. These large scale simulations are ideal to naturally probe the maximum, saturation scales of particle acceleration.

Taken together, PIC and MHD approaches are complementary: PIC is well suited to tackle injection from sub-rest-mass energies up to a few hundred mc^2 (notably in pair plasmas), whereas MHD captures the macroscopic acceleration up to the highest observed energies at the turbulence-injection scale, with particular relevance for protons.

Finally, reconnection-driven acceleration offers a compelling framework for the high-energy output of AGNs. In what follows, we examine this process in that context, with emphasis on the MHD perspective.

2. Plasmoid versus Turbulence-driven Reconnection in MHD Flows

The prevailing view that tearing-mode instability initiates plasmoid cascades leading to fast, resistivity independent, reconnection is challenged by recent results. To investigate the development of tearing-mode driven reconnection, [30] performed the highest-resolution 2D MHD simulations of reconnecting current sheets, for Lundquist numbers $10^3 \leq S \leq 2{\times}10^5$ ($S = Lv_A/\eta$, where η is the magnetic resistivity, L the scale of the system and v_A the Alfvén speed)[see also 31]. The authors in [30] find that plasmoids generated by tearing-mode instability are quickly advected out of the reconnection layer rather than forming a cascade. Reconnection remains resistivity (S) dependent

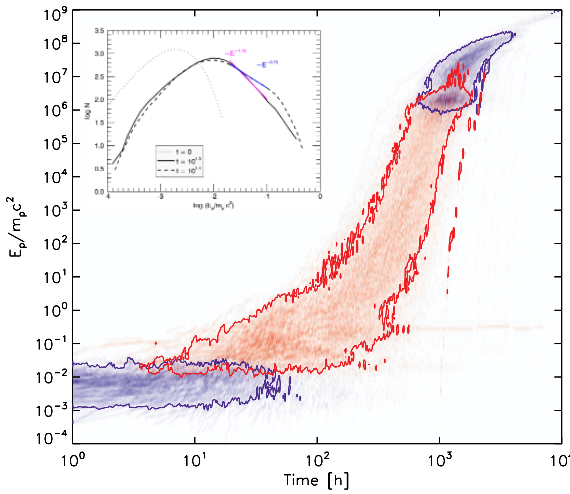

Figure 1: Kinetic energy evolution histogram, normalized by the proton rest mass energy, for CRs injected in a 3D relativistic jet where fast reconnection layers are produced by CDK turbulence, similarly as in Figure 2. The colors indicate the dominant velocity component being accelerated: red for the component parallel and blue for the component perpendicular to the local magnetic field. The red regions correspond to the Fermi acceleration regime, where particle energy grows exponentially with time, while the blue regions represent the drift acceleration regime. In the Fermi regime, particles can reach energies $\gtrsim 10^{16}$ eV, sufficient to produce gamma rays and neutrinos in AGN jets. The inset displays the particle energy spectrum as a function of normalized kinetic energy at two early time steps of the acceleration (in hours). The dotted gray line is the initial Maxwellian distribution. Extracted from [8].

and slow, with the reconnection velocity $v_{\rm rec} \sim S^{-1/3}$. This challenges the widely held view that plasmoid cascades enable fast, S-independent reconnection, and calls for a reassessment of the role of plasmoids in 2D high-S reconnection.

By contrast, turbulence-driven reconnection produces velocities v_{rec} that are independent of resistivity and depend solely on the turbulence velocity and injection scale [23]. Recent high-resolution 3D MHD resistive simulations have demonstrated that the reconnection velocity is much higher in turbulence-driven reconnection than in tearing-mode- (or plasmoid-) driven reconnection, indicating the predominance of turbulence-driven reconnection in such flows [32].

3. Particle Acceleration within reconnection layers

It is widely accepted that particles are accelerated within reconnection sites (current sheets, CS) through a first-order Fermi process [1, 9, 33]. In this regime, particles bounce back and forth and gain energy ($\Delta E/E \simeq v_{rec}/c$), while interacting with magnetic fluctuations, between the two converging magnetic fluxes of opposite polarity [1]. Once their Larmor radius exceeds the CS thickness, they can undergo further acceleration outside the sheet via drift in the gradients of the non-reconnected magnetic field. While the Fermi process primarily enhances the parallel momentum of particles, the drift mechanism increases their perpendicular momentum [14, 16, 18, 19].

Both 3D MHD and 3D MHD-PIC simulations of turbulence-driven reconnection with test particles in different environments, including relativistic jets, have confirmed these theoretical predictions [8, 16, 17, 19, 21, 22]. They have shown that, in the Fermi regime, acceleration proceeds inside the reconnection layer until the Larmor radius approaches the turbulence injection scale, which also sets the thickness of the largest reconnection layers. In this stage, energy grows exponentially with time, as expected from a Fermi process, and particles attain very large energies. Beyond this threshold, particles may still continue to gain energy via drift in large-scale non-reconnecting fields, though at a slower, energy-dependent rate. The resulting spectra typically develop a high-energy tail with an index ~ -1 to -2, shaped by the combined action of Fermi and drift acceleration. Figure 1 illustrates the results of one such study, showing particles accelerated to PeV energies and beyond by turbulence-driven magnetic reconnection in a magnetized relativistic jet, similar to the one depicted in Figure 2 (left panel).

In contrast, recent 3D PIC simulations have suggested drift-dominated particle energy spectra at large energies [14, 34]. This remains a subject of debate [e.g., 35]. Since drift acceleration is strongly energy-dependent and inefficient at the highest energies, it is unlikely to explain the observed ultra-high energy particles by this process, thus cautioning against straightforward extrapolations from PIC scales to macroscopic astrophysical environments [22].

The particle acceleration rate, $t_{\rm acc}^{-1}$, is a crucial parameter in magnetic reconnection theory. Within turbulence-driven reconnection layers, this is governed by the first-order Fermi process [1], as stressed. This rate is independent of particle energy [8, 19, 21], but depends on the current sheet (CS) parameters, namely its thickness Δ, the reconnection velocity $v_{\rm rec}$, and the angle between the guide field and the reconnected field. Recently, [36] revisited this dependence and identified three distinct regimes for $t_{\rm acc}$. They showed that the fastest acceleration occurs when both $v_{\rm rec}$ and the angle are large, yielding $t_{\rm acc} \simeq \frac{4\Delta}{cd}$, where $d \approx \frac{2\beta_{\rm in}(3\beta_{\rm in}^2+3\beta_{\rm in}+1)}{3(\beta_{\rm in}+0.5)(1-\beta_{\rm in}^2)}$, and $\beta_{in} = v_{rec}/c$.

In recent work, [22] numerically tested these conditions. Using simulations of magnetically dominated, turbulent relativistic jets, they investigated particle acceleration and derived acceleration times, comparing them with theoretical predictions for both the Fermi and drift regimes. Specifically, they examined the relations of [36] for Fermi acceleration within reconnection layers, employing statistical distributions of current sheet thicknesses and reconnection speeds identified with the reconnection-search algorithm described in [29]. They found that the average acceleration times agree well with the theoretical expectations, exhibiting only weak dependence on particle energy in the Fermi regime, as expected. This agreement was further validated through comparison with in situ acceleration times measured from 50,000 test particles, showing excellent consistency, particularly under the fastest reconnection time condition (Figure 2, right panel). When simulating longer acceleration periods in a quasi-steady turbulent jet snapshot, they observed that the Fermi regime maintains nearly constant acceleration times up to a critical energy, where the particle Larmor radius matches the thickness of the largest current sheets. Beyond this threshold, particles transition to the drift regime, where acceleration time becomes strongly energy-dependent, as anticipated. Overall, the results confirm the theoretical framework and demonstrate the dominance of the Fermi acceleration process up to very high energies.

3.1 Implications for VHE emission in Jets and Accretion disks

The results above are compelling, as the derived acceleration rates provide crucial insight into probing the VHE spectra of relativistic jets and accretion flows. For example, multiple radiative

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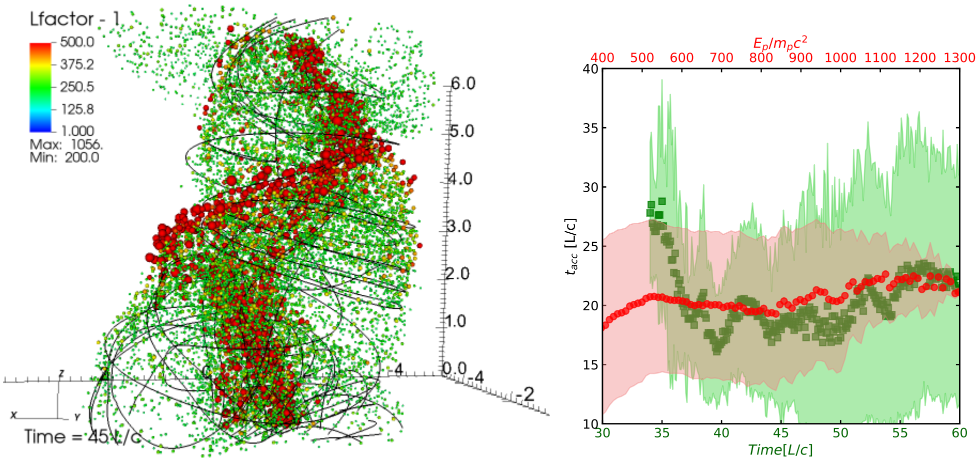

Figure 2: Left panel: 3D view of a simulated relativistic jet at snapshot $t = 45$ L/c, where L is the length unit of the jet ($2L$ gives the initial jet radius). The black lines represent the magnetic field. The circles represent the particles kinetic energy normalized by the rest mass energy ($\gamma_p - 1$) larger than or equal to 200. The growing circles reflect increasing energy as well as the change of colors (from green to red). Right panel: average particle acceleration time calculated from two independent methods. In red: the acceleration time, as a function of both the particle kinetic energy (normalized by the proton rest mass energy) and the time, calculated directly from the particles accelerated in the MHD-PIC simulation of the jet ($t_{acc} = E/(dE/dt)$). In green: the acceleration time evolution, calculated directly from the fastest reconnection regions in the jet, identified with the reconnection-search algorithm [27, 29], using the relations of [36]. Extracted from [22].

scenarios have been proposed to explain the multi-messenger (MM) emission from TXS 0506+056 blazar. To assess the maximum potential for neutrino production at energies consistent with the observed IC-170922A event, [37] recently employed a hybrid lepto-hadronic model without external soft photons, assuming that turbulence-driven magnetic reconnection accelerates both protons and electrons via the Fermi process at the rate presented above. Within this framework, they modeled the evolution of the blazar jet at the transtion region from magnetically dominated to a kinetically dominated flow. As the emission region propagates downstream, it produces a sequence of SEDs that reproduce the 2017 MM flare of TXS 0506+056, with a neutrino–VHE time delay of ~ 6.4 days, consistent with observations [37]. The authors also applied this turbulence-driven reconnection model to Mrk 501. During July 2014, MAGIC observations revealed a TeV gamma-ray spike coincident with an X-ray flux enhancement, suggesting an additional emission component beyond the standard one-zone SSC scenario. While other explanations (e.g., stochastic acceleration, vacuum gaps, or pion decay) failed, their model accounts for this behavior through two leptonic emission regions within a reconnecting jet: a stable region producing the baseline emission and a smaller, more magnetized upstream region responsible for the transient X-ray flare and narrow TeV spike (Rodriguez-Ramirez et al., in prep.).

Finally, fast turbulence-driven magnetic reconnection in black hole coronal accretion flows can also accelerate particles to extreme energies [1, 5, 38], providing a natural explanation for the γ-ray and neutrino emission observed in LLAGNs, including the recent IceCube detection from NGC 1068 (see Passos-Reis et al. 2025, these Proceedings). This scenario is also supported by MHD and GR-MHD simulations [e.g. 27, 39].

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