# Ultra-high-energy cosmic ray acceleration by magnetic reconnection in relativistic jets and the origin of very high energy emission

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Relativistic jets are believed to be born magnetically dominated. Very and ultra-high energy cosmic rays can be efficiently accelerated by magnetic reconnection in these sources. We here demonstrate this directly, with no extrapolations to large scales, by means of three-dimensional relativistic magnetohydrodynamical (3D-RMHD) simulations of a Poyinting flux dominated jet. We inject thousands of low-energy protons in the region of a relativistic jet that corresponds to the transition from magnetically to kinetically dominated, where its magnetization parameter is $\sigma \sim 1$. In this region, there is efficient fast magnetic reconnection which is naturally driven by current-driven-kink instability (CDKI) turbulence in the helical magnetic fields of the jet. We find that the particles are accelerated by Fermi process in the reconnection regions (and by drift in the final stages) up to energies $E \sim 10^{18}$ eV for background magnetic fields $B \sim 0.1$ G, and $E \sim 10^{20}$ eV for $B \sim 10$ G. We have also derived from the simulations the acceleration rate due to magnetic reconnection which has a weak dependence on the particles energy $r_{acc} \propto E^{-0.1}$, characteristic of exponential growth. The energy spectrum of the accelerated particles develops a power-law tail with spectral index $p \sim -1.2$. This hardness of the spectrum must decrease when particle losses and feedback into the background plasma are included. Our results can explain observed flux variability in the emission of blazars at the very high energy band as well as the associated neutrino emission. Successful applications of our results to the blazars MRK 421 and TXS 0506+056 are also discussed.

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*Presenter

## 1. Introduction

Relativistic Jets are born magnetically dominated and perhaps the most striking evidence on this has been recently provided by the EHT polarization measurements in the surrounds of the supermassive black hole of the active galaxy M87 [1]. Directly connected to this fact is that the observations of several blazars (active galactic nuclei, AGN, with highly beamed relativistic jets pointing to the line of sight) have evidenced very high energy (VHE) emission with time-variability of minutes in the TeV bands (e.g., PKS 2155-304 [2]), implying extremely compact and fast emission regions with Lorentz factors much larger than the typical bulk values in the jet of these sources ($\Gamma_{bulk} \simeq$ 5–10). This is very hard to be explained by standard particle acceleration in shocks, particularly if it comes from the magnetically dominated inner jet regions of these sources. Indeed, the only mechanism that seems to be able to explain both, the high variability and compactness of the TeV emission in these sources is particle acceleration in magnetic reconnection layers to PeV or larger energies [3, 4]. Equally striking is the recent outstanding simultaneous detection of gamma-rays and high-energy neutrinos from the blazar TXS 0506+056 [5]. This has highlighted the potential efficiency of AGN jets as ultra-high-energy cosmic ray (UHECR) accelerators, evidencing for the first time the presence of high-energy protons interacting with ambient photons, producing pions that subsequently decay in gamma-rays and neutrinos. It has been speculated that if these protons are produced in the magnetically dominated regions of the jet near the source core, then they are most probably accelerated by fast magnetic reconnection [6].

Particle acceleration by magnetic reconnection has been explored in a broad context from the solar system [e.g. 7] to jets and accretion disks in microquasars and AGNs [e.g. 3, 4, 8–10, and references therein], pulsar wind nebulae [e.g. 11], and gamma-ray bursts (GRBs) [e.g. 12].

Magnetic reconnection occurs when magnetic fluxes of opposite polarity encounter, then partially break and rearrange their configuration at a velocity $V_{rec}$ which is a substantial fraction of the local Alfvén speed ($V_A$) if reconnection is fast [e.g. 13]. Different processes such as plasma instabilities, anomalous resistivity, and turbulence, may trigger fast reconnection. The latter process, in particular, is very efficient and probably the main driving mechanism of fast reconnection in large scale astrophysical flows [14]. Since turbulence causes an efficient field-fluid slippage and stochasticity of the magnetic field lines, bringing initially distant lines into close separations through Richardson diffusion [13], this leads to many patches reconnecting simultaneously, making the reconnection rate very fast (and actually independent of the intrinsic plasma microscopic magnetic resistivity and the Lundquist number).

The rearrangement of the magnetic field configuration converts magnetic into thermal and kinetic energies, and allows for efficient particle acceleration predominantly in a Fermi-like stochastic process [8] [see also reviews on this process, e.g. in 15].

Particle acceleration in reconnection regions has been successfully tested in several numerical works employing multi-dimensional (2D and 3D) magnetohydrodynamic (MHD) simulations with test particles [e.g., 4, 6, 16–18], and particle-in-cell (PIC) simulations [e.g. 7, 19–21, and references therein].

Both MHD and PIC simulations have probed the efficiency of particle acceleration by reconnection, but a fundamental difference is that while PIC simulations can probe only the microscopic scales of the process up to a few thousand of the plasma skin depth ($c/\omega_p$) and early acceleration

of the particles only up to a few $\sim 100$ times their rest mas ($mc^2$), the MHD simulations with test particles can probe the much larger scales of the astrophysical systems and accelerate the particles up to the observed UHEs, i.e. several orders of the magnitude of their rest mass [4, 16–18].

In this talk we summarize our recent results on the acceleration of thousands of test particles injected in a magnetized relativistic jet with the characteristics of a blazar jet, subject to current-driven kink instability (CDKI), based on 3D relativistic MHD simulations [4, 22]. We find that the particles can be accelerated up to UHEs in the regions of fast magnetic reconnection which are developed in the turbulent flow driven by the kink instability, thus demonstrating that these sources are really efficient UHECR accelerators [4]. The magnetic reconnection power associated to the events of fast reconnection is able to produce a variability pattern that is consistent with observed flux variability at the gamma-ray band of blazars (e.g. MRK 421) [22]. Finally, from these results we have also built a multi-zone lepton-hadronic model based on particle acceleration by magnetic reconnection which is able to reproduce the spectral energy distribution (SED) of the blazars, from BLLacs to FSRQs, including their VHE band and the neutrinos (Rodriguez-Ramirez et al., in prep.; see also Rodriguez-Ramirez et al. this Conference).

## 2. Magnetic reconnection and particle acceleration in blazar jets

Jets with strong helical or toroidal fields are subject to CDKI [see e.g. 23]. This instability distorts the jet column and induces non-helical currents that ultimately can break the magnetic field lines and drive magnetic reconnection.

In [4, 22], we performed 3D RMHD simulations of a mildly relativistic blazar jet employing the RAISHIN code [23] with an initial helical magnetic field configuration and a magnetization parameter $\sigma = B^2/\gamma^2 \rho h \sim 1$ (where $B$ is the magnetic field, $\gamma$ is the Lorentz factor, $\rho$ is the density and $h$ is the specific enthalpy). A precession perturbation induced the growth of the CDKI. Figure 1 presents snapshots of the simulated jet. We note the development of a wiggling structure along the jet spine as the CDKI grows. This distortion drives turbulence in the plasma and then the magnetic field lines undergo fast reconnection at different scales, in agreement with the turbulent reconnection theory [14]. The colored circles characterize the reconnection sites which are mathematically identified using a reconnection search algorithm [22, 24]. Figure 2 schematically shows how the algorithm identifies these reconnection regions. We find fast reconnection events with average reconnection velocities $V_{rec}/V_A \simeq 0.05$. The distributions of the reconnection events and of the magnetic field strength after the growth and saturation of the tubulence follow a turbulent spectrum [22]. These reconnection regions with fast rates at several scales are a key ingredient to allow for an efficient Fermi like particle acceleration [8].

When turbulence achieved saturation and a nearly stationary state, we injected in the simulated jet hundred to thousand protons with initial Maxwellian velocity distribution ($10^{-3} m_p c^2$, where $m_p$ is the proton mass and $c$ is the speed of light). The left panel of Figure 3 shows how the accelerated particles (orange squares) correlate with the magnetic reconnection layers (characterized by high current density) and the sites of fast reconnection (colored circles). The right panel of Figure 3 depicts the energy evolution of the particles in the nearly steady state jet with a maximum magnetic field $B_0 \sim 10$ G. Similarly to previous studies of test particles in single currents sheets [16–18], the injected particles in this simulation, after an initial slow drift in the varying background
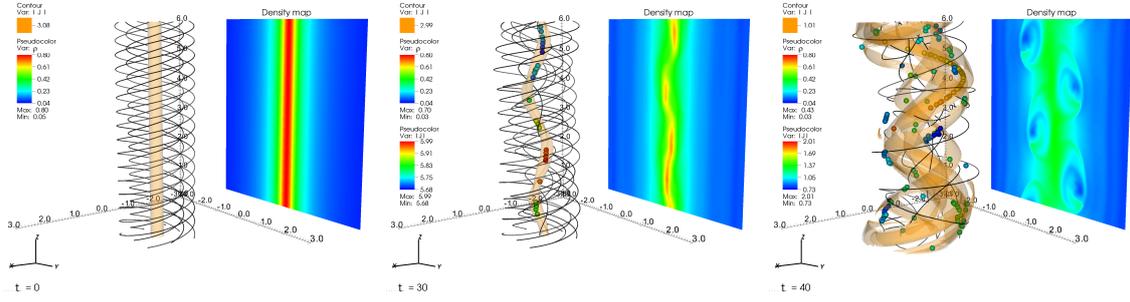
**Figure 1:** Time evolution of the jet at $t = 0$, $30$ and $40$ $L/c$ (from left to right). The diagrams depict isosurfaces of the current density intensity at half maximum $|J|$ (orange color), the solid black lines correspond to the magnetic field lines, the density profile at the middle of the box ($y - z$ plane at $x = 0$), and the magnetic reconnection sites identified by a search algorithm in the jet frame given by colored circles along the jet which correspond to different current density magnitudes in code units. From [4, 22].



*Observer Frame (primed variables)*  *Jet Frame*  *Reconnection Frame (tilded variables)*
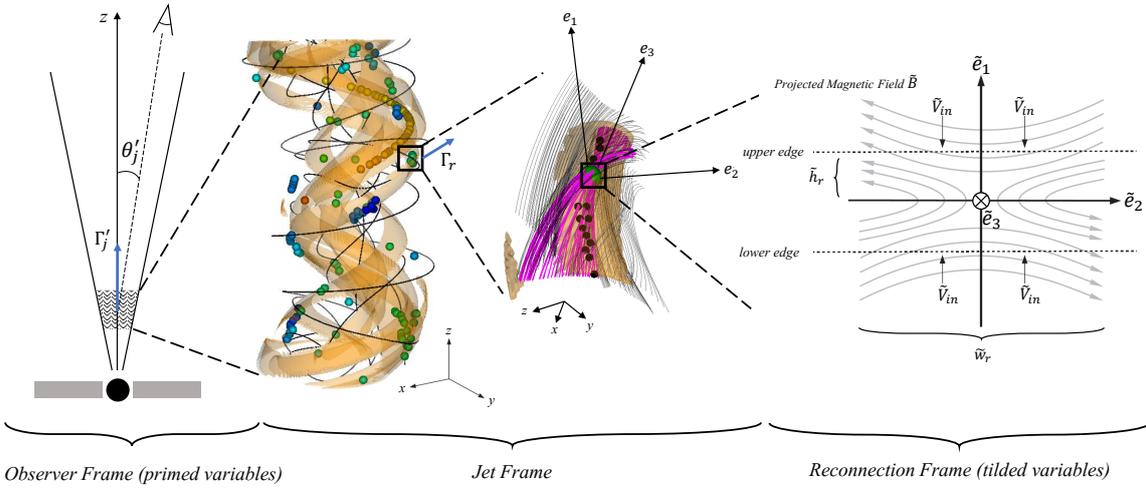
**Figure 2:** The first sketch (from the left to the right) shows the relativistic jet at the observer reference frame (primed variables). The hatched region corresponds to the simulation domain moving with an angle $\theta'_j$ to the line of sight and with a bulk Lorentz factor $\Gamma'_j$. In physical units, this region, identified as the dissipation region of the jet, has physical dimensions of the order of 0.1 pc. The second and third figures show the evolved structures of the simulation at the jet reference frame. The colored circles correspond to reconnection sites and the streamlines correspond to the magnetic field. Finally, the last sketch depicts the details of a reconnection region in a coordinate system at the reconnection reference frame (tilded variables), as used in the reconnection search algorithm. From [22].

field, undergo an exponential growth in their kinetic energy. This is due to the stochastic Fermi acceleration in the reconnection sites, as described in Section 1. This regime lasts for several hundred hours until a saturation energy around $\sim 10^9 m_p c^2$ or $\sim 10^{18}$ eV. During this time, the particles interact with magnetic fluctuations from the small resistive scales up to the injection scales of the turbulent structures driven by the CDKI, of the order of the distorted jet diameter. Beyond this value, their energy increases further up to $\sim 10^{20}$ eV, but in a slower, linear rate regime. At the end of the exponential acceleration the particles Larmor radius has achieved a value comparable to the jet diameter. Above this energy and Larmor radius, the particles are no longer confined by the magnetic discontinuities. Still, they undergo further acceleration due to magnetic drift in the large scale fields but at a linear rate. [1]

The particles energy distribution develop a power-law spectrum with spectral index $p \sim -1.2$, which is compatible with previous MHD and PIC studies. This hard spectrum reflects the absence of the particles feedback into the jet plasma and radiative losses which are not accounted for in such test particle simulations. Nevertheless, these losses are not expected to alter substantially the maximum energy achieved by the particles.

The simulations also provide the particle acceleration rate due to reconnection. It has a weak dependence on the particles energy $r_{acc} \propto E^{-0.1}$, which is comparable to earlier studies [e.g., 16–18], and expected in a Fermi process with nearly exponential energy growth in time. The results from Figure 3 imply a total acceleration time (including the exponential acceleration regime by reconnection plus the slower final drift acceleration) of a few $\sim 1000$ hr. During this time, particles have traveled a total length of the order of $\sim 10^{-1}$ pc along the jet. If we consider only the time elapsed during the acceleration exponential regime, the length scales are even smaller ($\sim 10^{-2}$ pc). These physical length scales characterize the size of the turbulent induced reconnection dissipation region in the jet where particles are accelerated and, within these (time and length) scales, the physical conditions in a real system are not expected to change substantially, except for the dissipation of the magnetic energy. It is interesting to note that these scales are compatible with estimates of the size of the reconnection dissipation/emission region inferred in other blazar studies.

In summary, our study has demonstrated from first principles, by means of 3D RMHD simulations with the characteristics of blazar jets, that these can produce UHECRs. The energies obtained, well beyond the expected PeVatrons, are more than sufficient to produce TeV gamma-rays and neutrinos in these systems. Our results may also explain the time flux variability in these systems. As an example, in Figure 4 we compare the observed power density spectrum (PDS) obtained from the light curve of the blazar MRK 421 [22, 25] in the energy band $0.1 - 300$ GeV, with our simulations. From the integrated magnetic reconnection power obtained from the simulated jet, we constructed the synthetic light curve and the PDS that is shown in Figure 4. These results suggest that the turbulent fast magnetic reconnection driven by CDKI is a plausible process behind the daily time-variability observed in the GeV band in this blazar.

In more recent work, we have also used the results described above to build a multi-zone lepton-hadronic model based on particle acceleration by magnetic reconnection, in order to reproduce the spectral energy distribution (SED) of blazars, from radio to gamma-rays and neutrinos. We have

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[1]For a background magnetic field $B_0 \sim 0.1$ G, we find that the particles are exponentially accelerated by reconnection up to $\sim 10^{16}$ eV and further accelerated by drift up to $\sim 10^{18}$ eV, i.e., for a field 100 times smaller, the maximum energy growth is 100 times smaller, as expected for the same maximum Lamor radius.
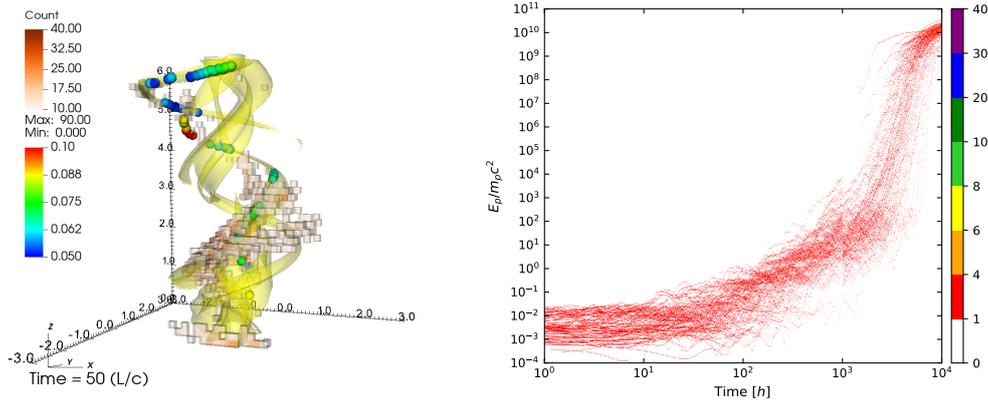
**Figure 3:** Left panel: 3D distribution of accelerated particle positions (square symbols) in an evolved snapshot of the jet model after the CDKI and the turbulence achieve a nearly steady state. Only particles accelerated with energy $E_p > 10^{-1}m_pc^2$ in the exponential regime (see right panel) are depicted. The circles correspond to the positions of fast magnetic reconnection sites. The isosurfaces of the current density intensity at half maximum $|J|$ (yellow color) are also depicted ($J_{max}/2 \sim 1.25$). Righ panel: kinetic energy evolution, normalized by the proton rest mass energy, for the particles injected in the steady state snapshot $t = 50\,L/c$ of the jet with a background magnetic field at the jet axis $B \sim 10$ G. (see [4] for details).
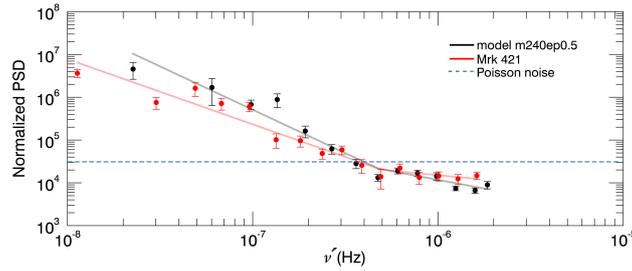


**Figure 4:** The diagram compares the normalized power spectral density (PSD) of the photon fluxe obtained from the light curve of MRK 421 [red line, obtained from 25] and that from our sumulated jet model (black line) in the observer frame. The blue traced line corresponds to the Poisson noise level for MRK 421. From [22].

accounted for all the relevant non-thermal radiative losses, including both leptonic (Synchrotron and inverse Compton) and hadronic processes (photo-pion production out of interactions with background photon fields, photo-hadron and photon-photon interactions with pair production). The results, applied, in particular, to the blazar TXS0506+056, indicate good agreement with the observations (see more details in Rodriguez-Ramirez et al., this Conference).

## Acknowledgments

6

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