PROCEEDINGS OF SCIENCE

Accelerated cosmic rays' feedback on relativistic jets

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This work focuses on computing the influence of particles accelerated by magnetic reconnection on the background plasma of relativistic jets, therefore, particle feedback. Recent works [1, 2] have focused on computing test particles (cosmic rays, CRs hereafter) acceleration by magnetic reconnection in relatvistic magnetohydrodynamic (RMHD) and RMHD particle-in-cell (RMHD-PIC) simulations of such jets, without accounting for their feedback on the background plasma. This influence on the resulting Lorentz force is yet to be determined in this class of simulations. We propose a post-processing strategy to account for such effects. In a first step, we employ RMHD-PIC simulations (using PLUTO code) performed in [2]; next, we fetch the particles' positions and velocities in desired snapshots and compute the Lorentz force attributed to them, following [3]. The current density for each cell in the mesh is computed according to the number of particles it contains. The average work performed by the particles and by the plasma on the system are computed, showing that the former is, on average, lower by a factor of $\sim 10^{-1}$, therefore only have influence not having much influence on the plasma dynamics or the particle acceleration process. Further studies are in development.

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1. Introduction

Magnetic reconnection happens when magnetic field lines of opposite polarities encounter each other, releasing energy in the process. In the presence of turbulence, this process is fast. The reconnection rate is a substantial fraction of the Alfvén velocity and indepedent of the microscopic resistivity [4]. This process has been successfully found in 3D MHD numerical simulations of classical and relativistic flows [5, 6]. It has been analytically demonstrated that particles can be accelerated in such fast reconnecting layers via a first-order Fermi process [7]. The efficiency of this process has been also probed numerically, both in non-relativistic 3D MHD flows [8–10] and in relativistic astrophysical jets [1, 2]. The particles undergo Fermi-like acceleration and can reach energies up to 10^{18} eV.

However, while Godunov-based MHD codes such as RAISHIN [11] or PLUTO [12] offer powerful numerical tools for these simulations, and in particular when combined with a PIC technique, the particles' feedback is not accounted for in the relativistic case. We propose a post-processing analysis to account for such feedback, following the formulation of [3].

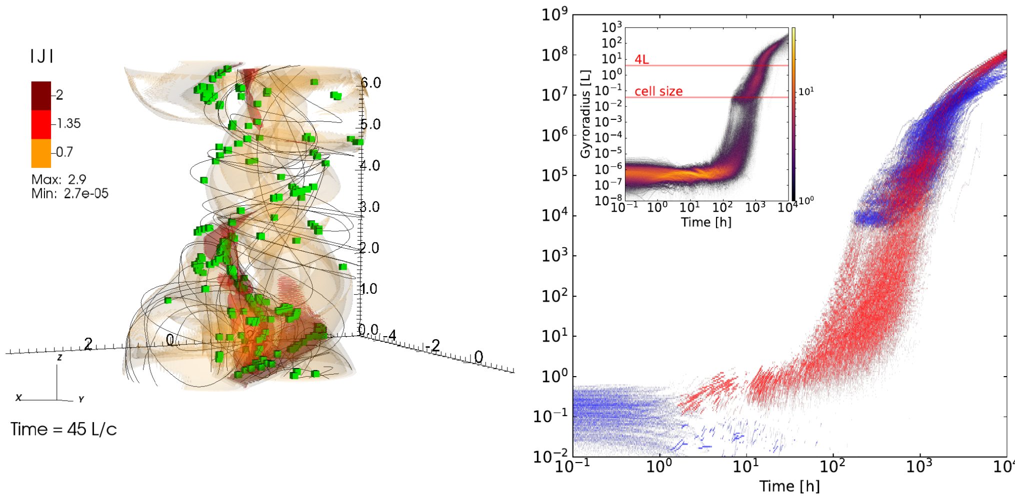

Figure 1: Left: 3D RMHD-PIC simulation: **fastest magnetic reconnection sites (in green) where particles are predominantly accelerated.** Black line represents the magnetic field and the orange area is the current density. Right: histogram of the particles kinetic energy growth with time when injected in a nearly steady state snapshot of the turbulent background jet on the left. Time is given in hours and the energy in units of rest mass of the particles (protons in this case). The inset gives the evolution of the gyroradius of the particles through time. **Extracted from** [1, 2].

2. Objectives

1. Implement the methods in [3] to compute particle feedback on 3D-RMHD-PIC simulation data from [2];

2. Quantify the influence of such feedback by computing the Lorenz force work performed by the particles and comparing this to that performed by the background plasma.

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3. Methodology

Data from simulations performed with PLUTO [12] by [2] was fetched. The **code** implements the RMHD equations and solves them for each time step:

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{pmatrix} + \nabla \cdot \begin{pmatrix} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{v}\boldsymbol{v} - \boldsymbol{b}\boldsymbol{b} + \boldsymbol{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \\ 0 \end{pmatrix}, \tag{1}$$

where D and $\boldsymbol{m}$ are the laboratory and momentum densities, respectively, and E_t and $\boldsymbol{f}_g$ are the total energy and external force terms, respectively. The term w_t represents the total enthalpy density. $\boldsymbol{v}$ is the velocity of the plasma and $\boldsymbol{B}$ is the magnetic field. γ is the Lorentz factor, p_t is the total pressure and $\boldsymbol{I}$ is the identity operator. The term $\boldsymbol{b}$ is given by $\boldsymbol{b} = \boldsymbol{B}/\gamma + \gamma(\boldsymbol{v}\cdot\boldsymbol{B})\boldsymbol{v}$. The box has $L = [6, 6, 10]$ with a resolution of 256 in all directions, with the simulation running until $t = 60$ in code units. 50,000 particles are injected and the magnetic reconnetion zones are identified. For more details see [1, 2, 13].

We define the current densities for the jet as

$$\boldsymbol{J} = \nabla \times \boldsymbol{B}, \tag{2}$$

where $\boldsymbol{B}$ is the plasma magnetic field, and, for particles with velocity $\boldsymbol{v}_p$ and position $\boldsymbol{x}_p$, as

$$\boldsymbol{J}_i = \sum_p cW(\boldsymbol{x_i} - \boldsymbol{x_p})\alpha_p\rho_p\boldsymbol{v}_p, \tag{3}$$

with $\alpha_p = (e/mc)_p$ being the CR charge-to-mass ratio and ρ_p being the mass density contribution of a single particle. i is index of the cell where the current density is being calculated and W is the Triangular Shape Cloud (TSC) weight function:

$$W_{i\pm1} = \frac{1}{2}\left(\frac{1}{2} \pm \delta\right)^2; \qquad W_i = \frac{3}{4} - \delta^2, \tag{4}$$

where $\delta = (x_p - x_i)/\Delta x$ is the distance between the particle and the i-esimal zone, and $\delta \in [-1/2, 1/2]$.

To analyze the results, we compute the average particle-to-jet work ratio (PJWR) in each time step k, averaged over the simulation volume, defined as

$$\mathrm{PJWR}_k = \frac{\text{Particle's average work}}{\text{Background's average work}} = \frac{\langle \boldsymbol{v}_{CR}\cdot(\boldsymbol{J}_{CR}\times\boldsymbol{B})\rangle_k}{\langle \boldsymbol{v}\cdot(\boldsymbol{J}\times\boldsymbol{B})\rangle_k}. \tag{5}$$

In the equation above, the numerator represents the average work of all the particles in a given snapshot. Such work is computed for each particle in each cell, than summed up to have a final work per cell per time step, then averaged. The same holds for the background's work, represented by the denominator in the above equation: for each cell in each time step, the work is computed based on the velocity of the background plasma and its current density, then the work is averaged over all the cells.

Since this is an RMHD simulation where only a distribution of super-thermal protons is injected to interact with the background plasma and undergo particle acceleration, the electric part of the Lorentz force is neglected.

4. Results

We first analyze the growth of average velocities and Lorentz force terms in each time step, for both jet and particles. Whereas particle's 3-velocities are $\sim 10^0$ higher than the jet's (see Figure 2).

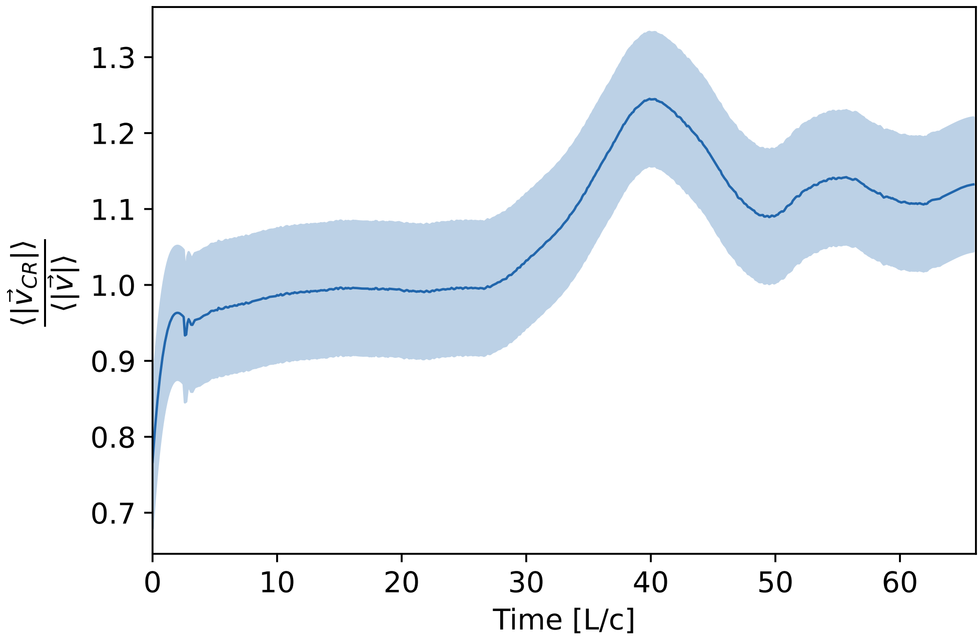

Figure 2: Average particle-to-jet 3-velocity ratio per time step.

The work of the jet is negative throughout the whole simulation, meaning that it gives energy to the particles. Its magnitude is also higher than the CR's work. When comparing both terms, the particle-to-jet work ratio is, on average, negligible, as shown in Figure 3.

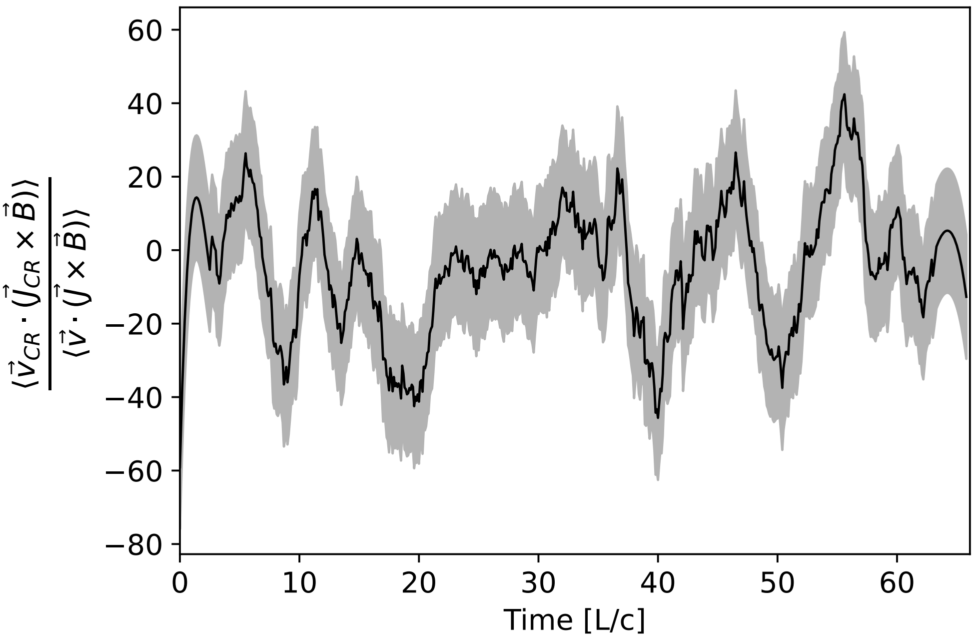

Figure 3: Average particle-to-jet work ratio per time step. Average is ~ -0.34.

5. Conclusions

We have found that, while the jet plasma is able to accelerate the particles up to ultra-high energies (Medina-Torrejon et al. 2021, 2023; Figure 1), the back-reaction of the particles on the jet plasma is negligible and does not produce considerable changes in its dynamics. This was assessed by comparing the work performed by the particles and that of the jet. We also expect that these losses will not influence the resulting power law spectrum of the particles calculated in [1, 2], and further studies are still in development.

Acknowledgements

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