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Computing particle feedback in RMHD-PIC simulations of relativistic jets

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Abstract. This work focuses on computing the influence of particles accelerated by magnetic reconnection in the background plasma of relativistic jets, therefore particle feedback. Recent works 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 perform RMHD-PIC simulations (employing PLUTO code); next, we fetch the particles' positions and velocities in desired snapshots and compute the Lorentz force attributed to them, following Bai et al. (2015). The average particle-to-jet work ratio - PJWR - performed by the particles and by the plasma on the system are computed, showing that the former is lower by a factor of $\sim 10^{-1}$, therefore not having, on average, much influence on the plasma dynamics or the particle acceleration process.

Resumo. Este trabalho foca em calcular a inluência de partículas aceleradas por reconexão magnética no plasma de jatos relativísticos. Trabalhos recentes na literatura focaram em computar a aceleração de partículas-teste (raios cósmicos) por reconexão magnética em simulações de magnetohidrodinâmica relativística (RMHD), incluindo também métodos particle-in-cell (PIC-RMHD), mas sem considerar a interação partícula-plasma. Tal interação na força de Lorentz resultante ainda precisa ser determinada em códigos como o PLUTO ou RAISHIN, que são comumentes utilizados neste tipo de simulação. Nós propomos uma estratégia pós-processamento para analisar estes efeitos. Primeiro, realizamos simulações PIC-RMHD com o PLUTO; após isso, selecionamos as posições e velocidades das partículas em cada intervalo de tempo da simulação e computamos a força de Lorentz seguindo Bai et al. (2015). O trabalho médio realizado pelas partículas sobre o plasma é então obtido, sendo da ordem de $\sim 10^{-1}$, não tendo, na média, muita influência no processo de aceleração do plasma ou da partícula.

Keywords. Magnetohydrodynamics (MHD) – Acceleration of particles – Magnetic reconnection

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 (Lazarian e Vishniac, 1999). This process has been successfully found in 3D MHD numerical simulations of classical and relativistic flows (Kowal et al, 2009; Takamoto et al., 2015). It has been analytically demonstrated that particles can be accelerated in such fast reconnecting layers via a first-order Fermi process (de Gouveia dal Pino e Lazarian, 2005. The efficiency of this process has been also probed numerically, both in non-relativistic 3D MHD flows (Kowal et al., 2011; kowal et al., 2012, del Valle et al., 2016) and in relativistic astrophysical jets (Medina-Torrejon et al., 2021; Medina-Torrejon et al., 2023). The particles undergo Fermi-like acceleration and can reach energies up to 10^{18} eV.

However, while Godunov-based MHD codes such as RAISHIN (Mizuno et al., 2012 or PLUTO (Mignone et al., 2018) 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 (Bai et al., 2015).

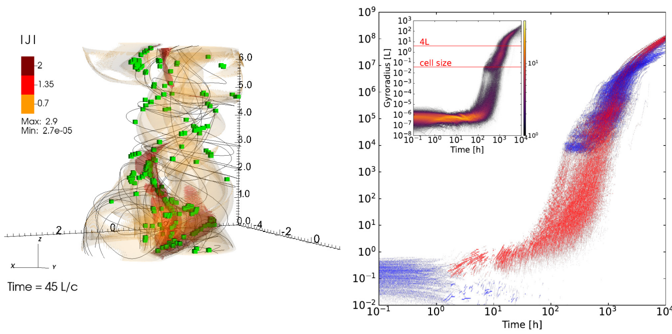

Figure 1. Left: 3D RMHD-PIC simulation: particles are accelerated in fast magnetic reconnection sites represented by green squares. Right: histogram of the particles kinetic energy growth with time when injected in the nearly steady state snapshot of the turbulent background jet on the left. (Medina-Torrejon et al., 2021; Medina-Torrejon et al., 2023)

2. Objectives

1. Implement the methods in Bai et al. (2015) to compute particle feedback on 3D-RMHD-PIC simulation data from Medina-Torrejon et al. (2023);
2. Quantify the influence of such feedback by computing the Lorentz force work performed by the particles and comparing this to that performed by the background plasma.

3. Methodology

Data from simulations performed with PLUTO (mignone et al., 2018 by Medina-Torrejon et al. (2023) was fetched. The software implements the RMHD equations and solves them for each time step:

$$\frac{\partial}{\partial t}\begin{pmatrix} D \\ \boldsymbol{m} \\ E_t \\ \boldsymbol{B} \end{pmatrix} + \nabla \cdot \begin{pmatrix} D\boldsymbol{v} \\ w_t\gamma^2\boldsymbol{vv} - \boldsymbol{bb} + \boldsymbol{I}p_t \\ \boldsymbol{m} \\ \boldsymbol{vB} - \boldsymbol{Bv} \end{pmatrix}^T = \begin{pmatrix} 0 \\ \boldsymbol{f}_g \\ \boldsymbol{v}\cdot\boldsymbol{f}_g \\ 0 \end{pmatrix}, \quad (1)$$

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. γ is the Lorentz factor, p_t is the total pressure and $\boldsymbol{I}$ is the identity operator. 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 (Medina-Torrejon et al., 2021; Medina-Torrejon et al., 2023; Kadowaki et al., 2021).

We define the current densities for the jet and for particles with velocity $\boldsymbol{v}_p$ and position $\boldsymbol{x}_p$ as

$$\boldsymbol{J} = \nabla \times \boldsymbol{B}, \quad (2)$$

where $\boldsymbol{B}$ is the plasma magnetic field, and

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

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:

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

where $\delta = (x_p - x_i)/\Delta x$ is the distance between the particle and the i-esimal zone, and $\delta \in [-1/2, 1/2]$. The work due to the Lorentz force can then be calculated as $\boldsymbol{v}_k \cdot (\boldsymbol{J}_k \times \boldsymbol{B})$.

4. Results

We first analyze the growth of average velocities and Lorentz force terms in each time step, for both jet an particles. Whereas particle's velocities are $\sim 10^0$ higher than the jet's, the interaction with the Lorentz force makes the work, on average, -0.34.

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 on Figure 3.

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.

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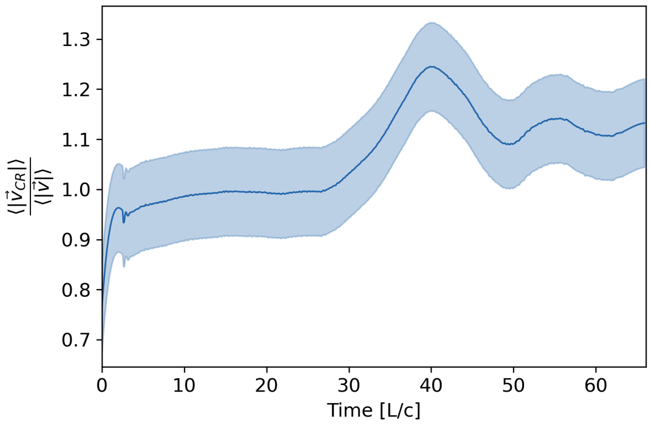

Figure 2. Average velocities per time step.

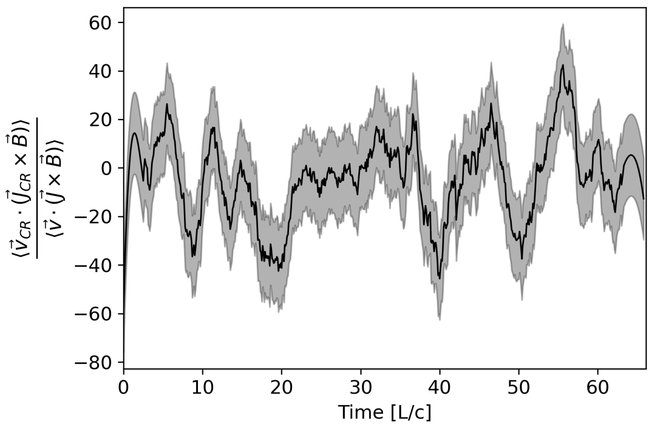

Figure 3. Average particle-to-jet work ratio per time step.

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