Gamma-ray flares from magnetic reconnection in relativistically magnetized plasmas: minijets vs. plasmoids

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The main cosmic sources of high-energy (HE; GeV-scale) gamma-ray radiation are: (1) blazars, the most luminous class of active galactic nuclei (AGN), the broad-band emission of which is produced in powerful narrowly collimated jets attaining relativistic bulk speeds and anchored at supermassive black holes; (2) pulsars (rotating neutron stars with strong magnetic fields) and associated wind nebulae (PWN). These sources are also characterized by strong time variability, with rapid gamma-ray flares posing a particular theoretical challenge. A common feature of these gamma-ray emitters is relativistically magnetized collisionless plasma. Efficient gamma-ray emission requires an efficient mechanism of energy dissipation and non-thermal particle acceleration, and relativistic magnetic reconnection is a primary candidate. To explain the production of rapid gamma-ray flares, two aspects of magnetic reconnection received particular attention: outflows from the magnetic diffusion regions attaining relativistic bulk velocities – so-called minijets, and plasmoids (flux ropes) resulting from the tearing instability. The relative importance of minijets and plasmoids was investigated [9] by means of particle-in-cell (PIC) numerical simulations of antiparallel magnetic fields in relativistically magnetized plasma. The algorithm includes radiative cooling due to synchrotron process, and radiative signatures in the form of observer-dependent light curves were calculated. It was demonstrated that minijets and plasmoids co-exist in the same reconnection layer. While minijets can accelerate particles to higher energies, plasmoids dominate the radiative output due to higher particle densities. Hierarchical tail-on plasmoid mergers (smaller and faster plasmoids capturing larger plasmoids) can explain the production of rapid gamma-ray flares.

Introduction

The gamma-ray sky is populated by a large number of point sources, the majority of which are associated with blazars (a class of cosmologically distant extremely luminous active galaxies), another major type of sources are pulsars (rapidly rotating magnetized neutron stars in our Galaxy) and associated wind nebulae [1]. Production of rapid gamma-ray emission requires an efficient mechanism of particle acceleration powered by dissipation of some form of energy. Magnetic reconnection operating in relativistically magnetized collisionless plasmas is a leading candidate. Interest in magnetic reconnection has been driven by observations of incoherent

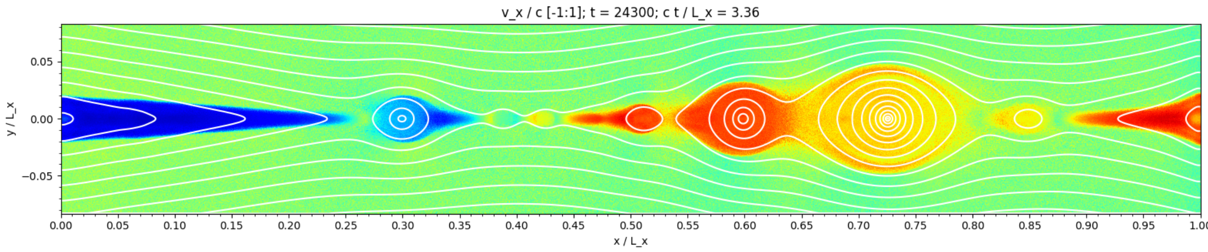

Figure 1: Snapshot from a 2D PIC simulation [9] of magnetic reconnection in relativistic pair plasma with outflowing left/right boundaries. The color indicates the horizontal velocity component v_x/c: blue means propagation to the left ($v_x < 0$), red means propagation to the right ($v_x > 0$), green means that $|v_x| \ll c$. The white lines are the in-plane magnetic field lines (contours of A_z). A minijet directed to the left can be seen for $x/L_x < 0.25$. Two plasmoids propagating to the right can be seen for $0.55 < x/L_x < 0.80$, the one on the left is smaller and faster (deeper red color), it is about to merge with the larger plasmoid tail-on.

gamma-ray flares characterized by very rapid variability, e.g. [2] in the case of blazars and [11] in the case of pulsar wind nebulae. Two particular structures produced by large-scale reconnection have been investigated:

- **Minijets** are relativistic Alfvénic outflows from the magnetic diffusion regions, they have been proposed to explain the rapid gamma-ray flares of blazars by providing additional relativistic boost of radiation within a larger relativistic jet [4]. Their structure can be based on the relativistic version of the Petschek model of reconnection developed in [7]. A detailed semi-analytical model of their radiative properties has been described in [**?**].
- **Plasmoids**, also known as magnetic islands, are compact regions of closed magnetic field lines. Plasmoids arise from the tearing mode of instability characterizing elongated current sheets [6]. In relativistic reconnection, they are dynamic structures that can be easily accelerated to relativistic speeds. Plasmoids evolve by collecting plasma and magnetic flux from reconnection outflows and by mergers with other plasmoids, forming hierarchical chains [10]. They have also been proposed to produce rapid flares of blazars [5].

Method

In [9], we have investigated the process of magnetic reconnection in relativistically magnetized plasma by means of 2D PIC simulations, using the `Zeltron` code (created by Benoît Cerutti; `http://benoit.cerutti.free.fr/Zeltron/`). The simulations were initiated from a single Harris current sheet for background magnetization $\sigma_0 = B_0^2/(4\pi n_\mathrm{b}\Theta_\mathrm{b} m_\mathrm{e} c^2) = 10$ with

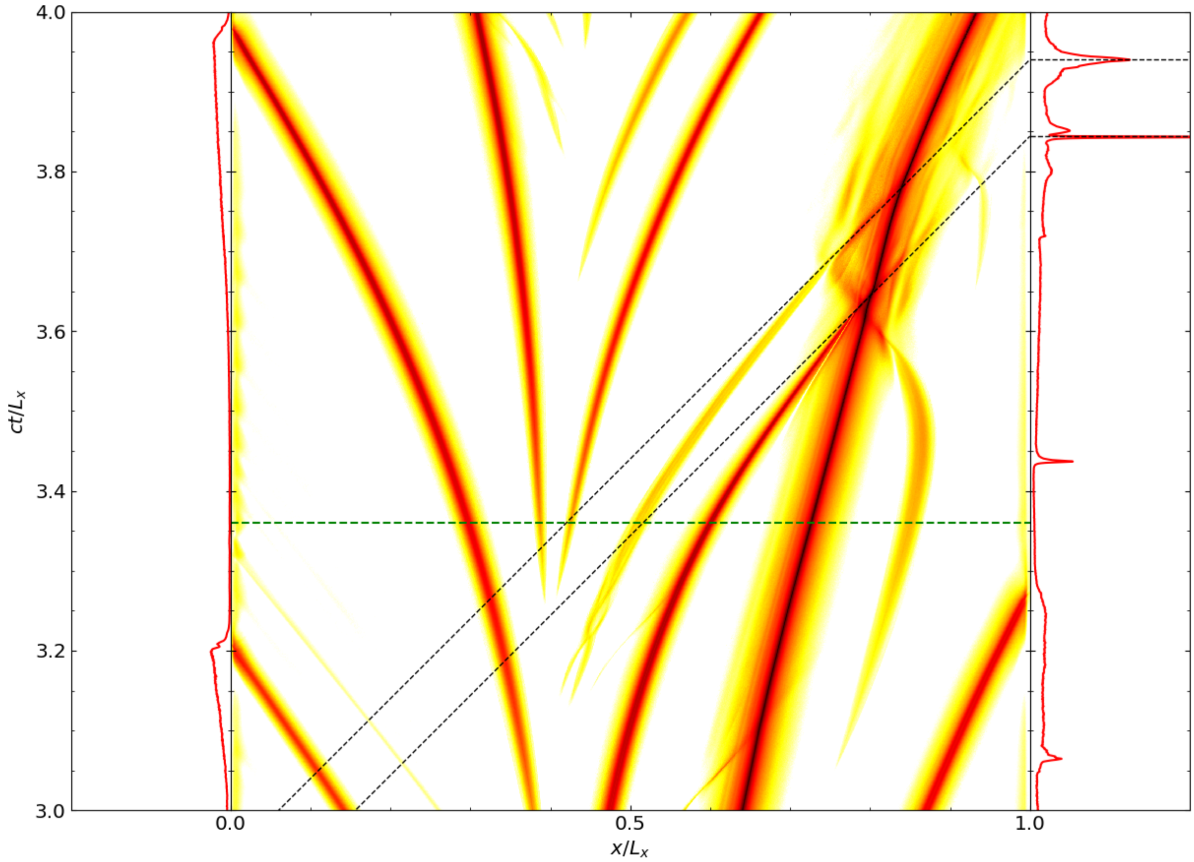

Figure 2: The middle panel shows spacetime diagram of synchrotron emissivity along a simulated reconnection layer. The green dashed line corresponds to the snapshot shown in Figure 1. The left and right panels show synchrotron light curves measured by observers located on either side of the layer. The black dashed lines indicate light cones corresponding to two flares seen by the observer to the right. Modified from [8].

no guide field. Following [10], we used outflowing boundaries that absorb electromagnetic structures propagating along the reconnection layer and remove the associated plasma. This allows to achieve steady-state reconnection with continuous production of new plasmoids. We also applied the radiation reaction force due to synchrotron process during every Boris push of particle momenta. We set ultra-relativistic temperature $\Theta_\mathrm{b} = k_\mathrm{B}T_\mathrm{b}/m_\mathrm{e}c^2 = 5\times10^5$ of the initial Maxwell-Jüttner distribution of particle energies in order to achieve efficient synchrotron cooling.

Results

Plasmoids are regions or strong magnetic field and high particle density. Low-density regions between plasmoids can be identified as the minijets. A plasmoid passing along a minijet does not disrupt it, the minijet reforms quickly in the plasmoid wake. Hence, plasmoids and minijets co-exist in the same reconnection layer (Figure 1).

Both minijets and plasmoids are the sites of particle acceleration. In minijets, particles can achieve high energies by propagating on Speiser orbits. In plasmoids, particles accelerate more slowly when orbiting around the magnetic O-point. In contrast to the non-relativistic mechanism of [3], plasmoids in relativistic reconnection circularize quickly, however, converging magnetic mirrors may form due to plasma inflowing onto the plasmoids from opposite directions [8].

The maximum particle energies are lower in the plasmoids compared to the minijets, they are also more strongly limited by synchrotron cooling. However, the plasmoids produce stronger signals of synchrotron radiation, which is due to their higher particle density. Rapid flares of synchrotron radiation can be produced during plasmoids mergers, even when the merging plasmoids propagate in the same direction (Figure 2). Because smaller plasmoids achieve higher bulk velocities, they are able to intercept larger plasmoids and merge tail-on.

This contribution was supported by the Polish National Science Centre grants 2015/18/E/ST9/00580 and 2021/41/B/ST9/04306.

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