PROCEEDINGS OF SCIENCE

Magnetic Reconnection: how this mechanism could explain the most extreme process in the universe?

Eloisa Menegoni,[a,b,*] **Paolo Buratti,**[b] **Valerio Vittorini,**[b] **Luca Foffano**[b] **and Marco Tavani**[b,c,d,e]

[a] *Agenzia Spaziale Italiana (ASI), via del Politecnico snc, I-00133 Roma (Italy);*
[b] *INAF - IAPS, via del Fosso del Cavaliere 100, I-00133 Roma (Italy);*
[c] *Astronomia, Accademia Nazionale dei Lincei, via della Lungara 10, I-00165 Roma, Italy;*
[d] *Università "Tor Vergata", Dipartimento di Fisica, via della Ricerca Scientifica 1, I-00133 Roma, Italy;*
[e] *Gran Sasso Science Institute, viale Francesco Crispi 7, I-67100 L'Aquila, Italy.*

E-mail: eloisa.menegoni@asi.it

There is an enormous number of astrophysical objects that emits powerful outbursts high-energy radiation with non-thermal spectrum like Pulsar Wind Nebulae(PWNe) and Blazars. Non-thermal processes are still not completely understood in theoretical plasma astrophysics. The ideal Magnetic Hydrodynamics (MHD) is not always able to explain recent observations on Crab Nebula and Blazars. Magnetic Reconnection (MR) is one of the candidates which could explain the most explosive phenomena seen in our Universe. Magnetic Reconnection mechanism modify the topology inside plasma, it changes the magnetic field lines inside the plasma, this extremely rapid changes causes the conversion of magnetic energy into kinetic energy: the particles acquire acceleration and they can impulsively deliver energy stored for long times and in large volumes. We will present some results from simulations obtained by using Zeltron public code based on PIC technique to explain some transient phenomena such as those observed in the Crab Nebula and Blazars.

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1. Introduction

Plasma physics is still an open and charming field of research, in particular, plasma mechanisms are fundamental to explain the most important observations in high-energy astrophysics. We investigate plasma mechanisms inside astrophysical sources with the aim to study non-thermal signatures observed by experiments like AGILE and FERMI, with applications both to galactic and extragalactic sources (PWNe, blazars, pulsars, etc...). The High-energy radiation detected from objects like Pulsar Wind Nebulae (PWNe) and Blazars is often observed to show a non-thermal spectrum, characterized by power laws behavior, this implies a strict relation between the emitting particle's energy and the resulting photon energy. The ideal Magnetic Hydrodynamics (MHD) is not able to explain this signature, so it is necessary to introduce different models to explain observations, such as, for example, the discovery of a new particle acceleration mechanism within the Crab Nebula done by AGILE [4, 7] and Fermi [9]. Particles acceleration inside an astrophysical source can be produced only by the application of an electric field, however, the release of high-energy bursts, as for example the synchrotron above the burn-off limit, can not be explained using only the electric field, we need to address our attention also to the magnetic field. **Magnetic Reconnection** could be the solution to this problem. This phenomenon implies extremely rapid changes in plasma topology which induce a violent breakup in the magnetic field lines, thanks to that the magnetic energy inside the plasma is transferred into particles kinetic energy. In particular, Reconnection has to be fast, and "Fast Magnetic Reconnection" is one of the key mechanisms which can induce the observational discoveries not already understood. The most energetic flares can be caused by the so-called "Fast Reconnection", which implies that plasma is very diluted and without Coulomb collisions (see for details [1–3, 17]). In our theoretical and simulation approach we will use this condition, in fact, the absence of collisions is satisfied in the most astrophysical cases.

2. Theoretical landscape

Magnetic Reconnection can be described as the process where the magnetic field lines are modified due to the presence of a localized diffusion region. This phenomenon leads to two main consequences: the first one is the conversion of magnetic energy into bulk kinetic energy (thermal energy and super-thermal particle energy), and, the second one, causes a topological change of the macroscopic magnetic field configuration. We follow a Sweet-Parker model to describe Magnetic Reconnection, in this model the diffusion region is elongated into plasma sheets, and, the particles can go back and forth along the Reconnection layer. This last mechanism allow particles to gain energy and after that they are accelerated in points, called X-points. The X-points are formed thanks to the fast changes in the magnetic field, in particular, the process occurs when magnetic field lines rapidly tear and rejoin, this fast mechanism induce a "flick" on the particles, which results in accelerating to relativistic speeds. The particles are accelerated with the emission of energy, and, at the same time we see the origin of magnetic islands, called plasmoids. The energy dissipation mechanism can be studied with the Vlasov equations [1]: the time evolution of particles inside the astrophysical plasma is fundamental to understand the non-thermal emission observed in the spectra. For astrophysical objects of our interest we know that the particle spectrum is composed by two components, one induced by Compton effect and the other one by the synchrotron mechanism.

We will focus our attention on the last one. The synchrotron energy emission inside an astrophysical source is ruled by the relation: $E^{max}_{sync} = (9mc^2/4\alpha)(E/B_\perp)$, where mc^2 is the electron rest mass energy, α the fine structure constant, E is the electric field and $B_\perp$ is the perpendicular direction component of the magnetic field. A theoretical description - not exhaustive - can be found in [1, 2, 5, 12–16].

3. PIC simulations: results

We perform different series of 2D two-dimension runs. We will present simulations using different initial conditions by using Zeltron public code [1], in particular, results from 2 anti-parallel current sheets with periodic boundary conditions. In this simulations we chose some parameters to be static, and, we change values of others. The 2D-PIC simulations provide an explanation for the extreme particle acceleration on layers, however, they are a simplified model of the 3D process inside the astrophysical sources. We will investigate 3D case in future works.

Parameter	Sim1	Sim2	Sim3	Sim4
N_{cells}	300	300	1200	1200
PPC	100	100	100	100
n_{drift}/n_{bg}	0.1	0.01	0.1	0.1
σ	16	16	16	149
β	0.6	0.6	0.6	0.6
T_{bg}	1.0	1.0	0.059	0.059
T_{de}	1.0	1.0	1.0	9.375
ρ	100 cm	100 cm	2000 cm	2000 cm
$L_x = L_y$	10000 cm	10000 cm	800000 cm	800000 cm

The PIC technique does not solve the Vlasov equation directly, PIC does not use semi-Lagrangian or Eulerian methods, but PIC models solve indirectly by integrating discrete particle trajectories. A description of the simulated plasma box can be found in [1, 5]): the box is divide in cells with a given number of particles for each cell. The Table shows the simulations setup. N_{cells} is the number of cells we used and PPC the number of particles inside each cell. Magnetization parameter is defined by the following relation:

$$\sigma = B_0^2/4\pi n_{bg}\gamma mc^2, \tag{1}$$

where $\gamma = eB_0\rho/mc^2$, ρ is the Larmor radius, and n_{bg} is the uniform density of isotropic non-thermal ultra-relativistic particles. We set different values for the background temperature T_{bg} and the temperature for drifting particles T_{de}. Our relativistic plasma is made up of electrons and positrons. Plasmoids and X-point formation can be seen only under the condition that electrons relativistic Larmor radius ρ is lower than the box dimension ($L_x = L_y$).

We present 2 groups of simulations results, the first one focusing on changing density ratio of particles (Sim1, Sim2), and, the second group focusing on changing the values of temperature

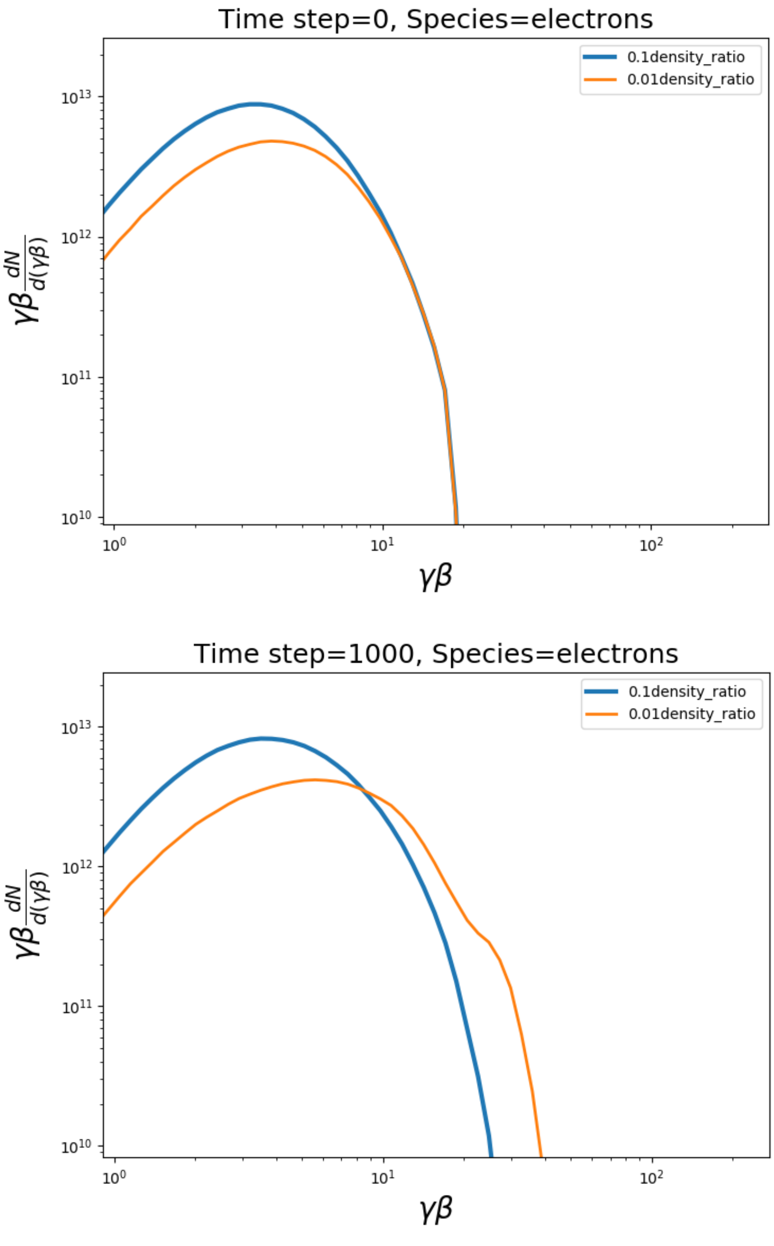

Figure 1: In this figure we show the time evolution of the particle spectrum for Sim1 and Sim2. The Sim2-case has a lower density ratio n_{bg}/n_0, for this case we see an hint of a power-law formation. The process starts at timestep around 800.

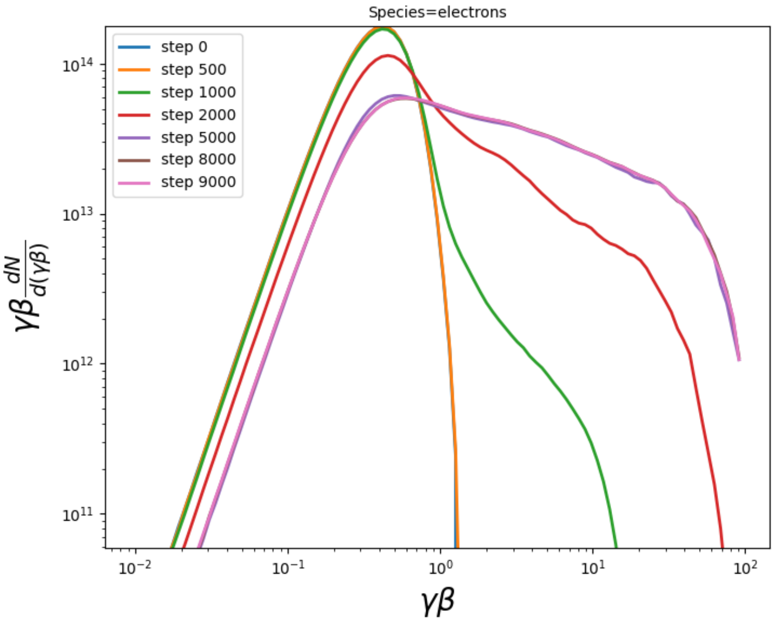

Figure 2: In this figure, we plot the timesteps overlap of particle spectrum for the case with $L_x = L_y = 800000cm$ (Sim3). At a given timestep value (i.e. = 1000), the particles Reconnection inside the plasma is faster for Sim3 than the case with smaller dimesion box (Sim1, Sim2 see figure 1) (see [11]).

(Sim3, Sim4) explained as follow. We perform 2D simulations with different values of the density ratio n_{bg}/n_0, where n_{bg} is the uniform density of isotropic non-thermal ultra-relativistic particles, and n_0 is defined as:

$$n_0 = \frac{kT_{drift}(1-\beta^2_{drift})^{1/2}}{4\pi e^2 \beta^2_{drift}\delta^2}, \tag{2}$$

where k is the Boltzmann constant, and T_{drift} is the drifting particles temperature in their comoving frame (for further details see [1]). The parameters setup values for "density ratio" simulations are in the first two columns of the Table (Sim1, Sim2). The third and fourth columns correspond to simulations with different values of temperatures (Sim3, Sim4).

The figure 1 shows the temporal evolution of the particle spectrum for both models Sim1 and Sim2. The Sim2-simulation shows an hint of a power law formation, this is the case in which the uniform density n_{bg} is lower than the previous one. If we compare the first two simulations (Sim1, Sim2) with the second group (Sim3, Sim4), we see that the Reconnection process is faster with box of larger dimensions. In the figure 3, the Reconnection mechanism is faster respect to Sim1, Sim2 (see figure 1), and Sim3 (see figure 2). At a given timestep value (= 1000), in fact, for Sim1 there is no power-law formation, however in Sim2 and Sim3 we see an initial origin of the phenomenon. The Sim4 shows the Magnetic Reconnection process to start at timestep around 300, and, by the end of simulation is completely done (timestep around 8000). For more details see [11].

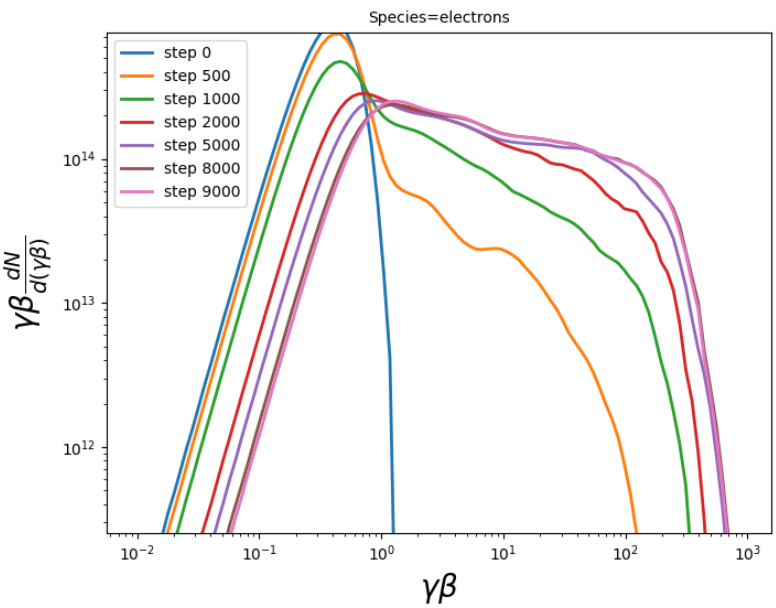

Figure 3: In this figure, we plot the timesteps overlap of particle spectrum for the case with $L_x = L_y = 800000cm$ (Sim4). The particles Reconnection inside the plasma is faster respect Sim1, Sim2 (see figure 1), and Sim3 (see figure 2). The Magnetic Reconnection process starts at timestep around 150 and by the end of simulation is completely done (see [11]).

4. Conclusions

We study the characteristic of magnetized plasma by using PIC models in order to clarify the unclear process that give birth to extreme events in our Universe. Magnetic Reconnection could explain the relativistic particle acceleration at high energy, in fact, it can be used to study some observations from astrophysics source like PWNs, blazars and Solar flares. In this work we shown that by decreasing the value of the density ratio n_{bg}/n_0, under same dimension box conditions, we see the formation of a power-law. However, this formation is not fast enough, for this reason we perform also simulation with boxes of larger dimensions. The Second groups of simulations (Sim3 and Sim4) shows the process of Magnetic Reconnection to be faster with higher values of temperature for drifting particles. In the last case (Sim4) higher values of T_{de} means higher value of magnetization, we need to achieve higher values of this parameter to see particle acceleration. These simulations are extremely expensive from the computational point of view and only with a powerful computational infrastructure is possible to obtains some results [5, 8]. We are performing similar simulations by using a more powerful infrastructure (PLEIADI), and by using different initial conditions to achieve more interesting results (for further details see [11]).

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