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In situ particle acceleration in collisionless shocks(*)

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Summary. — The outflows from gamma-ray bursts, active galactic nuclei and relativistic jets in general interact with the surrounding media through collisionless shocks. With three dimensional relativistic particle-in-cell simulations we investigate such shocks. The results from these experiments show that small-scale magnetic filaments with strengths of up to percents of equipartition are generated and that electrons are accelerated to power law distributions $N(\gamma) \propto \gamma^{-p}$ in the vicinity of the filaments through a new acceleration mechanism. The acceleration is locally confined, instantaneous and differs from recursive acceleration processes such as Fermi acceleration. We find that the proposed acceleration mechanism competes with thermalization and becomes important at high Lorentz factors.

PACS 52.27.Ny – Relativistic plasmas.
PACS 52.35.Qz – Microinstabilities (ion-acoustic, two-stream, loss-cone, beam-plasma, drift, ion- or electron-cyclotron, etc.).
PACS 52.35.Tc – Shock waves and discontinuities.
PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

Observations of astrophysical objects with relativistic plasma outflows generally show frequency spectra dominated by power law segments. These objects count gamma-ray bursts (GRBs) and active galactic nuclei. The general interpretations of such observations is that 1) electrons are accelerated to power law distributions $N(\gamma) \propto \gamma^{-p}$ in the collisionless shock interface between the relativistic ejecta and the surrounding media and 2) the accelerated electrons radiate through synchrotron radiation in the downstream region of the shock. The magnetic field strength required to account for the observed radiation spectra is typically of the order of percents of equipartition. A complete physical model for relativistic collisionless shocks should account for both the origin of such strong magnetic fields and for acceleration of electrons to power law distributions.

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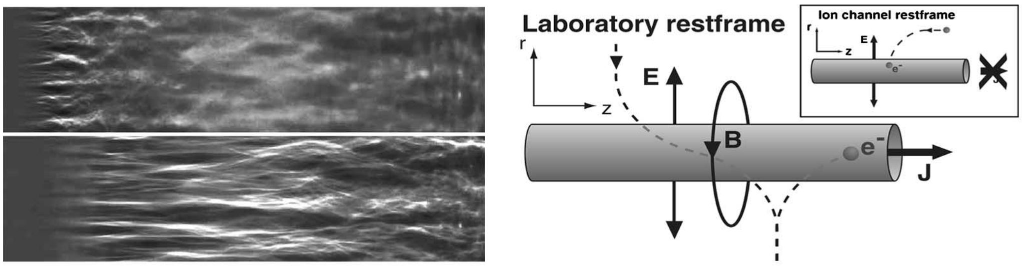

Fig. 1. – *Left panel:* The Weibel two-stream instability forms current channels. The electrons (*top panel*) undergo the instability faster the the heavier ions (*bottom panel*). *Right panel:* A schematic view of an ion current channel surrounded by an electric and a magnetic field. Electrons in the vicinity of the current channels are subject to a Lorentz force with both an electric and magnetic component, working together to accelerate the electrons along the ion flow. Crossing the center of the channel, the process reverses, leading to an oscillating movement along the channel.

Regarding the origin of the magnetic field, particle-in-cell (PIC) simulations have shown that the Weibel two-stream instability can generate a small scale, but strong, magnetic field transverse to the jet flow ($\epsilon_B \simeq 0.05$ where ϵ_B describes the fraction of total injected kinetic energy that is converted to magnetic energy) [1-5]. Other PIC simulations have found that the ambient large scale magnetic field neccesary to quench this instability has to be significantly stronger than the μG field typically found in the interstellar medium (ISM) [6, 7].

Regarding the non-thermal electron acceleration, Monte Carlo test-particle simulations have shown that Fermi acceleration can provide electron power law distributions under some assumptions about the shock and magnetic field [8]. This mechanism has, however, not been conclusively demonstrated to occur in ab initio particle simulations. PIC simulations have shown that both thermal and non-thermal particle acceleration take place in the shock transition region [9, 10, 4, 11].

In this paper, we discuss the particle dynamics in collisionless shocks based on results from a three dimensional relativistic PIC code. We propose a new particle acceleration mechanism that is itself a consequence of the Weibel two-stream instability [9].

2. – Numerical model and results

We have performed computer experiments using a charged particle-in-cell code. The code works from first principles by solving Maxwell's equations for the electromagnetic fields and the Lorentz force equation of motion for the particles. The fields are defined on a numerical grid and the particles are defined in a continuous phase space. We use a computational box with $125\times125\times2000$ grid points and a plasma consisting of 8×10^8 ions and electrons. The ion rest-frame plasma frequency is $\omega_{pi} = 0.075$, rendering the box 150 ion skin depths long. The electron rest-frame plasma frequency is $\omega_{pe} = 0.3$ in order to resolve the microphysics of the electrons. Hence, the ion-to-electron mass ratio is $m_i/m_e = 16$.

In the experiments we study the microphysics of two colliding plasma populations. The experiments are carried out in the rest frame of one of the populations (downstream, *e.g.*, a jet). In this frame, a less dense population (upstream, *e.g.* the ISM) is continuously injected at the leftmost boundary $z = 0$. We have performed two runs with relativistic velocities corresponding to Lorentz factors $\Gamma = 3$ and $\Gamma = 15$. Initially, the jet plasma is denser by a factor of three and both plasma populations are unmagnetized. The boundaries in the direction transverse to the jet flow (x, y) are periodic. At the z-boundaries, electromagnetic waves are absorbed and we allow particles to escape in order to avoid unphysical feedback. The experiment lasts until $t_{max} = 340\ \omega_{pi}^{-1}$, which is sufficient for the continuously injected upstream ISM-plasma to travel 2.3 times the length of the box.

The results from the experiments show how the Weibel two-stream instability forms current filaments in the region where the two plasma populations interpenetrate and how these filaments merge into increasingly larger patterns further downstream (fig. 1 *left panel*) (see also [1, 12, 4, 5]). The induced magnetic field grows to $\epsilon_B \simeq 1\%$. We identify two mechanism that accelerate electrons. The first is thermalization caused by random deflections by the generated small scale electromagnetic field. This mechanism is dominant for the $\Gamma = 3$ run. In the $\Gamma = 15$ run a second acceleration mechanism becomes important, which we briefly discuss in what follows; a more detailed description can be found in [9]).

The generated ion current channels are Debye shielded by the heated electrons. At distances less than the Debye length, the current channels are surrounded by transverse electric fields that accelerate the electrons toward the current channels. The acceleration happens in an approximately electrostatic field and is a simple consequence of potential energy being converted into kinetic energy. Therefore, the electrons are decelerated again when leaving the current channel and reach their maximal velocities at the centers of the current channels (fig. 1). It has been shown that a spatial Fourier decomposition of the transverse ion filaments in the box exhibits power law behavior [1,12]. Hence, the number of accelerated electrons is expected to reflect this power law behavior. This relation is confirmed in fig. 2. The left panel shows a scatter plot of electron momentum $(v\gamma)$ plotted against the strength of the electric current sampled at each electrons position. There is a power law correlation between the electron energy and the local current density. Some deviations from the power law are found: "Cold" trapped thermal electrons (indicated with the ellipse) exist inside the ion current channel and count towards lowering the average four velocity at high J_{ion}. Also, heated electrons are found outside the current channels which increase the average four velocity at low J_{ion}. The electron distribution function can be seen in the right panel of fig. 2. It shows a thermal distribution with a power law component at high energies. The slope of the power law segment corresponds to a spectral index of $p = 2.7$.

3. – Conclusions

We have investigated magnetic field generation and particle acceleration in collisionless shocks using three dimensional charged particle-in-cell experiments. The results are applicable to interactions between relativistic outflows and the interstellar medium. Such relativistic outflows occur in GRBs and in jets from compact objects.

We observe how the Weibel two-stream instability is excited and find that the nonlinear stage of the instability penetrates at least 150 ion skin depths into the shock ramp. Extrapolating to the real electron-ion mass ratio, this is more than 6000 electron skin depths. The instability efficiently creates a strong, small-scale magnetic field ($\epsilon_B \simeq 1\%$).

Regarding particle acceleration, the results show that thermalization dominates the electron distribution in the simulation run where a jet is expanding with $\Gamma = 3$. At $\Gamma = 15$, a new acceleration mechanism becomes important in the high energy tail of the spectrum. The acceleration is non-thermal and the resulting electron distribution function has a power law segment. The slope of this segment corresponds to $p = 2.7$.

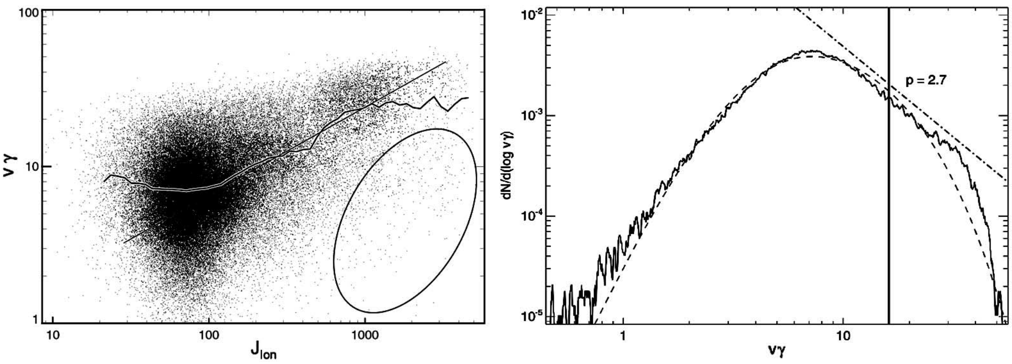

Fig. 2. – *Left panel:* A scatter plot of the local ion current density J_{ion} *vs.* the four-velocity of the electrons in a region downstream of the shock. Overplotted is a solid line showing the average four-velocity as a function of J_{ion}, and a dashed line showing a straight-line fit. *Right panel:* The normalized electron particle distribution function downstream of the shock. The dot-dashed line is a power law fit to the non-thermal high energy tail, while the dashed curve is a Lorentz-boosted thermal electron population. The horizontal line at $v\gamma = 15$ indicates the plasma injection velocity.

We emphasize that the generation of magnetic field and the non-thermal acceleration of electrons are two highly interconnected processes in collisionless shocks. The acceleration is closely tied to the spatial distribution of electric current filaments. Further large scale simulations are needed to determine how this slope depends on different parameters.

When the injected ISM ions have traveled through the simulation box they are not merged with the jet ions to a single population. This indicates that larger simulations are also required to cover the whole shock ramp.

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