Particle Acceleration, Magnetic Field Generation, and Emission in Relativistic Shocks

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Abstract

Shock acceleration is a ubiquitous phenomenon in astrophysical plasmas. Plasma waves and their associated instabilities (e.g., Buneman, Weibel and other two-stream instabilities) created in collisionless shocks are responsible for particle (electron, positron, and ion) acceleration. Using a 3-D relativistic electromagnetic particle (REMP) code, we have investigated particle acceleration associated with a relativistic jet front propagating into an ambient plasma. We find small differences in the results for no ambient and modest ambient magnetic fields. Simulations show that the Weibel instability created in the collisionless shock front accelerates jet and ambient particles both perpendicular and parallel to the jet propagation direction. The small scale magnetic field structure generated by the Weibel instability is appropriate to the generation of “jitter” radiation from deflected electrons (positrons) as opposed to synchrotron radiation. The jitter radiation resulting from small scale magnetic field structures may be important for understanding the complex time structure and spectral evolution observed in gamma-ray bursts or other astrophysical sources containing relativistic jets and relativistic collisionless shocks.

Key words: Relativistic shocks, Weibel instability, Particle acceleration, Magnetic field generation, Radiation

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1 Introduction

Nonthermal radiation observed from astrophysical systems containing relativistic jets and shocks, e.g., active galactic nuclei (AGNs), gamma-ray bursts (GRBs), and Galactic microquasar systems usually has power-law emission spectra. In most of these systems, the emission is thought to be generated by accelerated electrons through the synchrotron and/or inverse Compton mechanisms. Radiation from these systems is observed in the radio through the gamma-ray region. Radiation in optical and higher frequencies typically requires particle re-acceleration in order to counter radiative losses.

Particle-in-cell (PIC) simulations can shed light on the physical mechanism of particle acceleration that occurs in the complicated dynamics within relativistic shocks. Recent PIC simulations using injected relativistic electron-ion jets show that acceleration occurs within the downstream jet, rather than by the scattering of particles back and forth across the shock as in Fermi acceleration (Frederiksen et al. 2003, 2004; Hededal et al. 2004; Nishikawa et al. 2003, 2004, 2005). Silva et al. (2003) have presented simulations of the collision of two inter-penetrating electron-positron plasma shells as a model of an astrophysical collisionless shock. In the electron-positron simulations performed with counter-streaming jets (Silva et al. 2003), shock dynamics involving the propagating jet head (where Fermi acceleration may take place) was not investigated. In general, these independent simulations have confirmed that relativistic jets excite the Weibel instability (Weibel 1959). The Weibel instability generates current filaments and associated magnetic fields (Medvedev and Loeb 1999), and accelerates electrons (Silva et al. 2003; Frederiksen et al. 2003, 2004; Nishikawa et al. 2003, Hededal et al. 2004).

In this paper we present new simulation results of particle acceleration and magnetic field generation for relativistic electron-positron and electron-ion shocks using 3-D relativistic electromagnetic particle-in-cell (REMP) simulations. In our new simulations, electron-positron and electron-ion relativistic jets are injected into electron-positron and electron-ion plasmas in order to study the dynamics of a relativistic collisionless shock both with and without an initial ambient magnetic field.

2 Simulation Setup and results

Four simulations were performed using an 85 \times 85 \times 320 grid with a total of 180 million particles (27 particles/cell/species for the ambient plasma) and an electron skin depth, \( \lambda_{ce} = c/\omega_{pe} = 9.6\Delta \), where \( \omega_{pe} = (4\pi e^2 n_e/m_e)^{1/2} \) is the electron plasma frequency and \( \Delta \) is the grid size (Nishikawa et al. 2004). In two other simulations an electron-positron jet is injected into a magnetized and unmagnetized electron-positron ambient plasma and in two simulations
an electron-ion jet is injected into a magnetized and unmagnetized electron-ion ambient plasma. The choice of parameters and simulations allows comparison with previous simulations (Silva et al. 2003; Frederiksen et al. 2003, 2004; Hededal et al. 2004; Nishikawa et al. 2003, 2004, 2005).

The electron number density of the jet is \( n_b^{0.741} \), where \( n_b \) is the density of ambient (background) electrons. The average jet velocity \( v_j = 0.9798c \), and the Lorentz factor is 5 (2.5 MeV). The jets are cold \( (v_{j,th}^e = v_{j,th}^p = 0.01c \) and \( v_{j,th}^i = 0.0022c \)) in the rest frame of the ambient plasma. Electron-positron plasmas have mass ratio \( m_p/m_e \equiv m_{e^+/e^-} = 1 \) and electron-ion plasmas have \( m_i/m_e = 20 \). The electron and ion thermal velocities in the ambient plasmas are \( v_{e,th} = 0.1c \) and \( v_{i,th} = 0.022c \), respectively, where \( c \) is the speed of light. The time step \( \Delta t = 0.013/\omega_{pe} \), the ratio \( \omega_{pe}/\Omega_e = 11.5 \), and the Alfvén speed (for electrons) \( v_{Ae} \equiv (\Omega_e/\omega_{pe})c = 8.66 \times 10^{-2}c \). With the speed of an Alfvén wave given by \( v_A = [V_A^2/(1 + V_A^2/c^2)]^{1/2} = 6.10 \times 10^{-2}c \) where \( V_A \equiv [B^2/4\pi(n_em_e + n_mp_p)]^{1/2} = 6.12 \times 10^{-2}c \), the Alfvén Mach number \( M_A \equiv v_j/v_A = 16.0 \). With a magnetosonic speed \( v_{ms} \equiv (v_{th}^2 + v_A^2)^{1/2} = 0.132c \) the Magnetosonic Mach number \( M_{ms} \equiv v_j/v_{ms} = 7.406 \). At least approximately the appropriate relativistic Mach numbers multiply these values by the Lorentz factor. Thus, in an MHD approximation we are dealing with a high Mach number shock with \( \gamma M >> 1 \). The gyroradius of ambient electrons and positrons with \( v_\perp = v_{th} = 0.1c \) is \( 11.1\Delta = 1.154\lambda_{ce} \) (for ambient ions: \( 49.6\Delta = 5.16\lambda_{ce} \)). All the Mach numbers with electron-ion jets are approximately increased by \( \sqrt{m_i/m_e} = \sqrt{20} = 4.47 \).

Current filaments resulting from development of the Weibel instability behind the jet front are shown in Figs. 1a and 1b at time \( t = 28.8/\omega_{pe} \) for unmagnetized ambient plasmas. In case (a) an electron-positron jet is injected into an electron-positron ambient plasma. In case (b) an electron-ion jet is injected into an electron-ion ambient plasma. The maximum values of \( J_y \) are (a) 15.63 and (b) 10.7, respectively. The electron-positron jet shows larger amplitudes than the electron-ion jet at the same simulation time and magnetic fields reduce the maximum values, confirming previous simulation results (Nishikawa et al. 2004). The effect of weak ambient magnetic fields affects the growth rates of Weibel instability slightly as shown in Hededal and Nishikawa (2004).

The heating and acceleration of jet electrons in directions parallel and perpendicular to the flow is shown in Figure 1 for the electron-positron case (1c and 1e) and for the electron-ion case (1d and 1f). The jet electrons are split into two parts: the injected (blue: rear half \( Z < 160\Delta \)) and shocked (red: front half \( Z > 160\Delta \)). (The jet electrons are divided at \( Z \sim 160\Delta \).) Since in the case of electron-ion jet the Weibel instability grows slightly the blue curves in Figs. 1d and 1f are considered as the distributions of injected jet electrons. In both parallel and perpendicular distributions, jet electrons are
more accelerated in the electron-positron case than in the electron-ion case.

Fig. 1. Panels (a, c, e) and (b, d, f) refer to the electron-positron and electron-ion cases, respectively (unmagnetized cases). 2D images show the current density \( J_y \) at \( t = 28.8/\omega_{pe} \). Colors indicate the \( y \)-component of the current density, \( J_y \) [peak: (a) 15.6, (b) 10.7], and the arrows indicate \( J_z \) and \( J_x \). The injected (blue line) and shocked (red line) electron distributions are shown as a function of \( \gamma v_{\parallel} \) ((c) and (d)) and \( \gamma v_{\perp} \) (e and f) where \( \gamma = (1 - (v_{\parallel}^2 + v_{\perp}^2)/c^2)^{-1/2} \).

The electrons are deflected by the transverse magnetic fields \( (B_x, B_y) \) via the Lorentz force: \(-e(v \times B)\), generated by current filaments \( (J_z) \), which in turn enhance the transverse magnetic fields (Weibel 1959; Medvedev and Loeb 1999). The complicated filamented structures resulting from the electron Weibel instability have diameters on the order of the electron skin depth \( \lambda_{ce} = \)
9.6Δ). This is in good agreement with the prediction of \( \lambda \approx 2^{1/4}c \gamma_{th}^{1/2}/\omega_{pe} \approx 1.188 \lambda_{ce} = 11.4\Delta \) (Medvedev and Loeb 1999). Here, \( \gamma_{th} \approx 1 \) is a thermal Lorentz factor. The filaments are elongated along the direction of the electron-ion jets (b) (the z-direction, horizontal in Figure 1). However, in the electron-positron jets the current filaments have coalesced in the transverse direction in the nonlinear stage. The transverse current (\( J_x \)) in the electron-positron jets (a) shows significantly more transverse variation than in the electron-ion jets (b).

The acceleration of electrons has been reported in previous work (Silva et al. 2003; Frederiksen et al. 2003, 2004; Nishikawa et al. 2003, 2004, 2005; Hededal et al. 2004). We see that some of the kinetic energy (parallel velocity \( v_\parallel \approx v_j \)) of the jet electrons is transferred to the perpendicular velocity via the electric and magnetic fields generated by the Weibel instability as shown in Fig. 1. The strongest transverse and parallel acceleration of jet electrons accompanies the strongest deceleration of electron flow and occurs between \( z/\Delta = 210 - 240 \). The transverse acceleration in the electron-positron jets is over four times that in the electron-ion simulations. The strongest acceleration takes place around the maximum amplitude of perturbations due to the Weibel instability at \( z/\Delta \approx 220 \) as seen in Figs. 1a and 1b.

### 3 Summary and Discussion

We have performed self-consistent, three-dimensional relativistic particle simulations of relativistic electron-positron and electron-ion jets propagating into magnetized and unmagnetized electron-positron and electron-ion ambient plasmas. The main acceleration of electrons takes place in the region behind the shock front. Processes in the relativistic collisionless shock are dominated by structures produced by the Weibel instability. This instability is excited in the downstream region behind the jet head, where electron density perturbations lead to the formation of current filaments. The nonuniform electric field and magnetic field structures associated with these current filaments decelerate the jet electrons and positrons, while accelerating the ambient electrons and positrons, and accelerating (heating) the jet and ambient electrons and positrons in the transverse direction.

Other simulations with different skin depths and plasma frequencies show that the growth rate and spatial structure of current filaments generated by the Weibel instability scale with the plasma frequency and the skin depth (Nishikawa et al. 2004). An additional simulation in which an electron-ion jet is injected into a ambient plasma with perpendicular magnetic field shows magnetic reconnection due to the generation of an antiparallel magnetic field generated by bending of jet electron trajectories, consequently jet electrons are subject to strong non-thermal acceleration (Hededal and Nishikawa 2004).
These simulation studies have provided new insights for particle acceleration and magnetic field generation. Further research is required to develop radiation models based on these microscopic processes.

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