Parallel 3D Electromagnetic Particle-In-Cell Simulation for Relativistic Jets

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Abstract

The radiation from afterglows of gamma-ray bursts is generated in collisionless plasma shocks between a relativistic out flow and an ambient medium. The two main ingredients responsible for the radiation are high-energy, non-thermal electrons and a strong magnetic field. First-order Fermi acceleration (or diffusive shock acceleration, DSA) is normally believed to be responsible for the acceleration of the particles. In DSA, particles diffuse back and forth across the shock front and gain energy by scattering from the magnetohydrodynamics (MHD) waves. However, DSA needs a seed population of particles with energies well in excess of the thermal ones, because only these particles are capable for multiple crossing the shock front and effective scattering by magnetic turbulences. However, it is not apparent how the electrons can reach the threshold energy of DSA. It demands their kinetic energies be comparable to those of the ions. This is known as the electron injection problem. In the case of magnetized upstream, the injection of electrons is thought to be directly associated with the background motional electric field $E_0 = -\beta_0 \times B_0$. They may gain energy from the motional electric field while they gyrate surf around the shock front. Based on the barrier that reflects the electrons toward the upstream, thus capable them for repeatedly energizations, this process is known with distinct names. If the reflecting barrier has a magnetic source, the acceleration mechanism is named shock drift acceleration or SDA. If the barrier has an electrostatic source, the process is called shock surfing acceleration or SSA. Basically, the SSA process acts only in the electron-ion shocks, because electrostatic barrier would not be generated if the species have the same inertia. Magnetization parameter, obliquity angle of the upstream magnetic field with respect to the shock direction of propagation, and bulk Lorentz factor of the incoming stream may also play significant role in determining the responsible process for particle acceleration. The main question in report is: how does the electron ejection operate in unmagnetized electron-ion shocks?" Here, on the basis of a three-dimensional relativistic electromagnetic particle-in-cell code, we have analysed the Weibel-like instabilities, collisionless external shocks, and the electron injection acceleration associated with the unmagnetized relativistic jet propagating into an unmagnetized ambient plasma. The results of simulations demonstrate that the Weibel-like instabilities are responsible for generating and amplifying the dominantly transversal electromagnetic fields. In accordance with hydrodynamic shock systems, the shock consists of a reverse shock and forward shock separated by a contact discontinuity. The development and structure are controlled by the ion Weibel-like instabilities. The ion filaments are sources of strong transverse electromagnetic fields at both sides of the double shock structure over a length of 30 -100 ion skin depths. Electrons are heated up to a maximum energy $\epsilon_0 \sim \sqrt{\epsilon_B}$, where ϵ is the energy normalized to the total incoming energy. The shock-reflected ambient ions generate a double layer in the reverse shock transition region which evolves consequently into an electrostatic shock. In addition, a double layer is formed in the forward shock transition region because of the decelerated jet ions and ambient electrons. The simulations show strong electron acceleration that is required

for injecting the electrons into the DSA. The large energy stored in the jet ions causes the extreme electron acceleration. The double layers convert directed ion energy into directed electron energy, without heating up the plasma. Electrons can thus be accelerated by the double layers to much higher speeds than by a shock because the latter also transfers flow energy into heat. The electron distribution functions in the reverse shock and forward shock transition regions show power-law distributions with index $p = 1.8 - 2.6$.