On the influence of particle acceleration on the structure of low-Mach astrophysical shocks

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Background

Cosmic rays are charged particles, moving at relativistic speeds after being accelerated through interaction with astrophysical shocks. This process, known as diffusive shock acceleration (DSA), or Fermi acceleration [1, 2, 3], involves the particle repeatedly crossing the shock, picking up speed each time it is reflected by the local magnetic field.

So far, computer models of this particle-shock interaction have focussed primarily on high-Mach shocks [4, 5, i.a.], such as supernovae and stellar wind collisions. Here we concentrate instead on a different type of shock: Shocks with a low sonic Mach number and a high plasma-β, such as those that occur when galaxy clusters collide. Previous results [6], obtained with the particle-in-cell (PIC) method, showed that these shocks are capable of accelerating particles and may contribute to the cosmic ray spectrum, depending on the characteristics of the shock.

We now continue this work using a combined particle-in-cell (PIC) and magnetohydrodynamics (MHD) approach [7, 8]. This involves splitting the plasma into two components. The first, which comprises the majority of the local plasma, behaves as a thermal plasma and can be simulated using MHD. The second, much smaller component behaves non-thermally and is modelled using PIC. The two components interact self-consistently with each other through the local electromagnetic field. This approach allows us to simulate a much larger physical volume than would be possible with the more traditional PIC-only approach.

Method

The combined PIC and MHD approach is built on the assumption that the plasma is mostly thermal, with only a small non-thermal component. Under these circumstances, the thermal plasma can be simulated with the MHD method, for which we use the MPI-AMRVAC code [9]. Meanwhile, the non-thermal component can be described as a collection of particles, which occur in the same physical space. The interaction between the components occurs through the electro-magnetic field. (We neglect the kinetic interaction, assuming that the motion of the non-thermal particles through the thermal gas is non-collisional.) The electro-magnetic field exerts a force on the charged, non-thermal particles so that the equation of motion for a single particle can be described as: For each particle, the equation of motion is given by

$$\frac{\partial \mathbf{p}_{\mathrm{j}}}{\partial t} = q_{\mathrm{j}} \left(\mathbf{E} + \frac{\mathbf{u}_{\mathrm{j}}}{c} \times \mathbf{B} \right), \tag{1}$$

where $\mathbf{p}_{\mathrm{j}}$, q_{j} and $\mathbf{u}_{\mathrm{j}}$ are the momentum, charge, and velocity of a particle with index j, while $\mathbf{B}$ and $\mathbf{E}$ are the magnetic and electric fields. We solve this equation with the use of a relativistic version of the Boris-method [10].

In order to create a self-consistent description, we apply the same force, acting in the opposite direction, to the equation of motion of the thermal fluid, as well as adding the associated work-term to the energy equation. The presence of supra-thermal particles also influences the electric field, leading to a change in Ohm's law [7, 8], which becomes:

$$c\mathbf{E} = -((1-R)\mathbf{v} + R\mathbf{u}) \times \mathbf{B}, \tag{2}$$

where $\mathbf{v}$ is the velocity of the thermal plasma, $\mathbf{u}$ the average supra-thermal particle velocity, which is obtained by averaging the velocities of the particles in the grid cell, and R the ratio of the supra-thermal particle density to the total particle density (the sum of thermal and non-thermal particles). For a full derivation of the relevant equations, we refer to [7, 8].

Simulation

Unlike PIC and PIC-hybrid simulations, which typically start from a beam of plasma that hits a reflective wall and then follow the shock as it moves backward into the beam, we start form the analytical solution for a standing shock, obtained from the Rankine-Hugoniot conditions. We assume an upstream medium with a flow speed (in the rest frame of the downstream medium) of 0.052 c, a sonic-Mach number of 3.2, a plasma-β of 100, and the magnetic field at a 13° angle with the flow. These parameters are based on the model by [6]. Because our model treats the shock itself as an MHD phenomenon (i.e. a discontinuity) we cannot simulate the initial acceleration mechanism which takes particles out of the thermal distribution. Instead, we assume a fixed injection rate of 0.4 percent, which means that 0.4 percent of the particles that traverse the shock becomes supra-thermal. This is based directly on the results obtained with a PIC simulation by

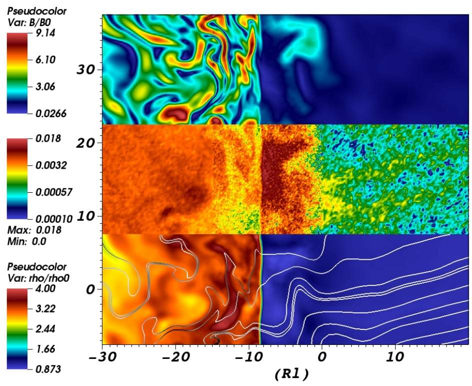

Figure 1: *The magnetic field strength, non-thermal gas density and thermal gas density for a Mach 3.2 shock after 2000 ion cyclotron times. the magnetic field in the upstream medium has become severely distorted.*

[6]. In our simulations, this supra-thermal injection is represented by the injection of particles at the location of the shock with a velocity of 3 times the pre-shock velocity as was also done in [8]. We inject only protons, assuming that all electrons behave as a thermal plasma. For this particular simulation, we assume a box that has a length of $2400\,R_l$ and a width of $15R_l$, with R_l the Gyro-radius defined by the upstream magnetic field and the injection velocity of the particles. The thermal gas flows in through the right-side boundary and out through the left-side boundary, while the upper and lower boundaries of the short axis are periodic.

Results

Figure 1 show the result of our simulation after 2000 ion cyclotron times (${\omega_{ci}}^{-}1$). This figure shows, from top to bottom, the magnetic field strength B relative to the unperturbed upstream magnetic field B_0, the non-thermal gas density q relative to the thermal gas density ρ, and the thermal gas density relative to the unperturbed upstream gas density ρ_0, as well as the magnetic field lines. The shock, which was initialized at x=0 has moved in the down-stream direction to approximately x=-8 as a result of energy loss in the downstream medium.The upstream medium (on the right) has become highly perturbed, showing considerable fluctuation in the strength and direction of the magnetic field. Meanwhile, the downstream medium shows clear evidence of turbulence.

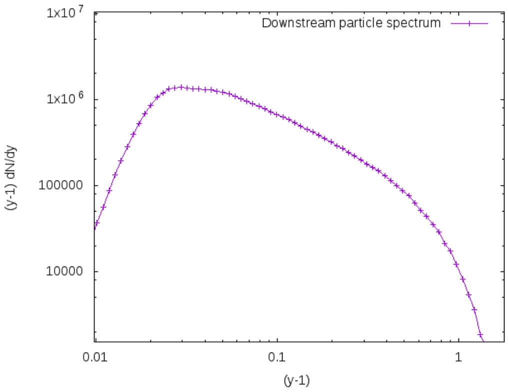

Figure 2: *Particle SED for the particles in the downstream medium at the same time as Fig. 1. Because the thermal plasma component is treated as a fluid, this SED shows only the non-thermal particles.*

In Fig. 2, we show spectral energy distribution (SED) of the non-thermal particles. at the same moment in time as Fig. 1. In this graph, we have plotted $(\gamma-1)$ on the horizontal axis with γ the Lorentz factor and $(\gamma-1)dN/d\gamma$ on the vertical axis. As shown by [6] for a shock with sonic Mach number 3.2, the particle SED for particles that are accelerated through DSA should scale with $(\gamma-1)$ to the power -1.72. However, this is only correct for non-relativistic particles. The particle SED for our simulation shows this behaviour over an interval that starts at $\gamma = 1.05$ and ends at approximately $\gamma = 1.5$. This proves that DSA is effective in this simulation and capable of accelerating particles at least to low relativistic speeds (For protons, a Lorentz factor of 1.5 indicates an energy of approximately $0.5\,\text{GeV}$). At this point the SED curves downward, partially as a result of less efficient acceleration and partially because the particles are becoming increasingly relativistic, which means their SED will no longer follow the scaling expected for non-relativistic particles. These results show that, a low-Mach, high-β shock, such as occurs during the merger of galaxy clusters, may be capable of accelerating ions to low relativistic speeds. However, our results also show that for these low-Mach, high-beta shocks, the particle acceleration process has a significant influence on the local plasma. Local instabilities, triggered by the interaction between the non-thermal particles and the magnetic field, change the medium ahead of the shock, in particular the angle between the shock surface and the magnetic field. This may well inhibit the injection of non-thermal particles into the local medium, effectively cutting off the acceleration process as PIC simulations by [6] indicate that the injection process may be inhibited at large angles. The upstream fluctuations will also influence the Mach number of the upstream medium, which in turn will influence the compression rate and therefore both the injection rate and the efficiency of the DSA process as shown by [6].

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