

# Diffusive shock acceleration of cosmic rays in low-Mach galaxy cluster shocks.

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**Abstract.** Astrophysical shocks are known to accelerate particles to high relativistic velocities. This process requires the particles to repeatedly cross the shock, a process that can only occur if the particle is reflected by the local magnetic field. Such particles are observed on Earth as cosmic rays. This phenomenon has been studied in considerable detail for high-Mach shocks, such as the shocks that occur in colliding stellar winds and supernova explosions, but remains relatively unexplored for low-Mach shocks, such as the shocks of colliding clusters of galaxies. Recent simulations using the particle-in-cell (PIC) method have shown that, depending on the exact Mach number, even low-Mach shocks can accelerate charged particles to the point where they start to deviate from the thermal velocity distribution. However, the computationally intensive nature of the PIC calculations makes it difficult to continue the simulations to determine whether the particles can reach relativistic speeds. We now present new simulations, using a combined PIC and magnetohydrodynamics (MHD) technique. This model, which takes advantage of the computational efficiency of MHD, allows us to simulate a much larger physical volume and study the behaviour of the particles over a longer period of time in order to determine to what extent the acceleration process continues and whether these shocks are capable of contributing to the cosmic ray spectrum

## 1. Background

When galaxy clusters collide, the interaction results in the formation of shocks that are characterized by a low sonic Mach number ( $M_S$ ) and a low plasma- $\beta$  (with  $\beta$  the magnetic energy density divided by the thermal energy density) [1, 2]. At this time it is unknown whether such shocks are capable of accelerating particles to relativistic speeds, which would allow them to contribute to the cosmic ray (CR) spectrum (e.g. see [3, 4, 5]).

Numerical models of high-Mach, low- $\beta$  shocks have shown that a small percentage of the ions that cross the shock become non-thermal (e.g.[6, 7, 8]). The interaction between these particles and the local magnetic field causes instabilities, which, in turn initiate the diffusive shock acceleration (DSA) process that continues to accelerate these particles through repeated shock crossings [9, 10, 11]. Recent particle-in-cell simulations [12] show that at least some low-Mach, high- $\beta$  shocks are capable of injecting supra-thermal ions as well. We need to investigate whether the DSA process can function under these circumstances and accelerate these particles to relativistic speeds, thereby contributing to the CR spectrum.



## 2. Method

### 2.1. Numerical approach

We treat the gas near the shock through a variation of the two-fluid approach, assuming that the plasma is mostly thermal, with only a small non-thermal component. As long as this condition is satisfied and the supra-thermal component remains small, relative to the thermal one, the thermal plasma can be simulated with the MHD method, using the MPI-AMRVAC code [13]. The non-thermal component can be described as a collection of particles, existing in the same physical space. Interaction between the components occurs only through the electro-magnetic field because we assume that the gas is non-collisional. Interaction between these two fluid components is handled in a self-consistent way: Because the non-thermal particles are charged, the electromagnetic field exerts a force on them and vice-versa. Furthermore, the presence of supra-thermal particles also influences the electric field, leading to a change in Ohm's law [14, 15]. For a full derivation of the relevant equations, as well as the method used to solve them, we refer to [14, 15].

### 2.2. Simulation setup

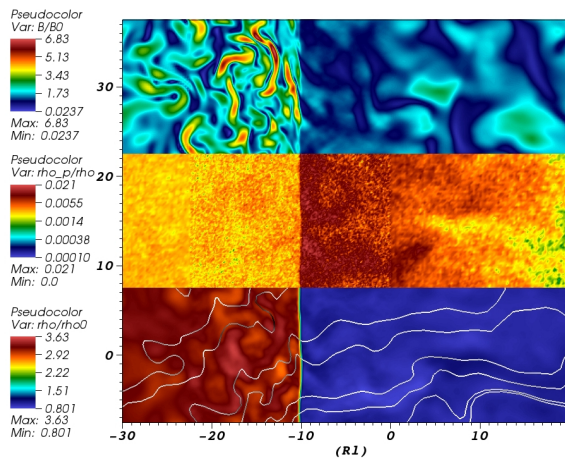
For our model we use a physical volume of  $2400 \times 15 R_l$ , with  $R_l$  the Gyro-radius defined by the upstream magnetic field and the initial velocity of the particles. At the right-hand boundary we introduce a constant inflow of gas, which passes through the shock and then continues downstream until it leaves through the left-hand boundary.

We start our simulation from the analytical solution for a standing shock, obtained from the Rankine-Hugoniot conditions [16], assuming that the upstream medium has a flow speed (in the downstream medium's rest frame) of  $0.052c$ ,  $M_S = 3.2$ , and plasma- $\beta = 100$ , with the upstream magnetic field at a  $13^\circ$  angle with the flow, copying the model by [12]. The combined PIC-MHD approach treats the shock itself as an MHD phenomenon (i.e. a discontinuity) Therefore, we cannot simulate the mechanism that accelerated particles out of the thermal distribution as they cross the shock. Instead, we assume a fixed injection rate of 0.4 percent, meaning that 0.4 percent of the particles traversing the shock becomes supra-thermal, based directly on the results obtained with a PIC simulation by [12]. This supra-thermal injection is represented by introducing particles at the location of the shock and with 3 times the pre-shock velocity [15]. We limit the supra-thermal component to protons, assuming the electrons remain thermalized.

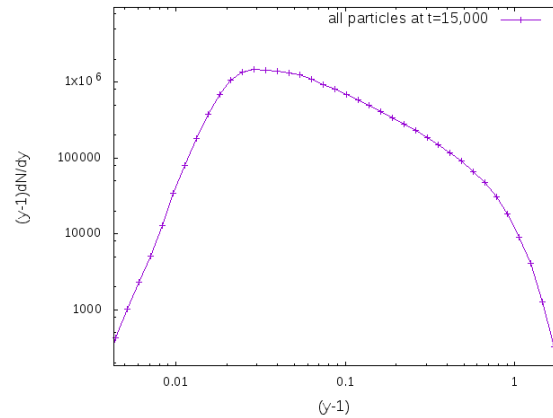
## 3. Result

As shown in Fig. 1 the presence of non-thermal particles excites instabilities in the upstream medium. These instabilities were identified as showing both resonant and non-resonant streaming instability characteristics [12]. This figure shows the magnetic field strength, non-thermal gas density and thermal gas density at the end of the simulation ( $t = 15\,000 R_l/c$ ). This in turn allows the DSA process to accelerate particles to higher velocities, as demonstrated in Fig. 2, which shows the particle SED as a function of  $(\gamma - 1)$ , with  $\gamma$  the Lorentz factor. The part of the curve with a fixed slope, indicating a powerlaw distribution, extends to approximately  $\gamma = 2$ , which, for protons, indicates a total energy of  $\gamma mc^2 \simeq 1.8 \text{ GeV}$ . Should such particles interact with thermal ions, they could produce gamma-radiation through pion decay. This would be visible as diffuse gamma radiation to instruments such as Fermi-LAT but observations, such as [17], show no evidence of such radiation.

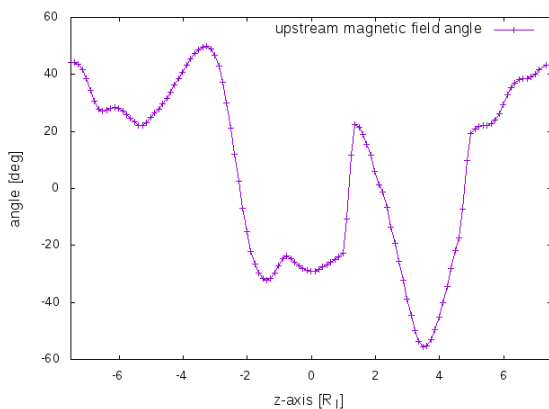
However, as seen in Fig. 1, the instabilities in the upstream magnetic field become so large that they start to change the nature of the shock. Figure 3 shows the angle between the magnetic field and the flow directly upstream of the shock as a function of the position perpendicular (z-axis) to the flow at the same moment in time as Figs. 1-2. Because the absolute angle, at times, becomes larger than 45 degrees, the shock can locally change from being semi-parallel to semi-perpendicular, with consequences for both the injection and acceleration process. Furthermore,



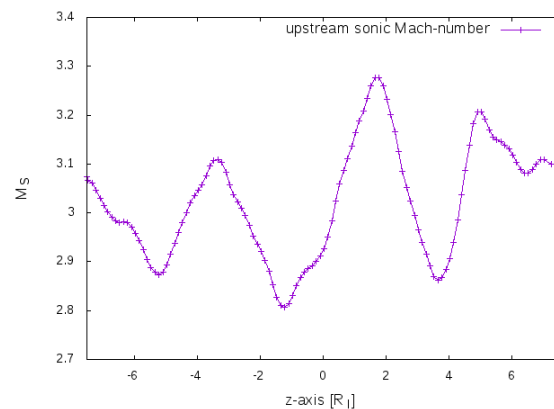
**Figure 1.** From top to bottom: absolute magnetic field strength relative to the unperturbed upstream field ( $B_0$ ), supra-thermal gas density relative to thermal gas density, and thermal gas density relative to the unperturbed upstream thermal gas density ( $\rho_0$ ) as well as the magnetic field lines at  $t = 15\,000 R_l/c$



**Figure 2.** Particle SED for the same point in time as Fig. 1, showing particle distribution as a function of the Lorentz factor  $\gamma$  minus one. The powerlaw slope that indicates DSA extends to approximately  $\gamma = 2$ .



**Figure 3.** The angle between the magnetic field and the flow directly upstream of the shock for the same moment in time as Figs. 1-2. The shock varies between semi-parallel and semi-perpendicular as a result of the upstream instabilities.



**Figure 4.** Sonic Mach number directly upstream of the shock at the same moment in time as Figs. 2-3. The compression of the magnetic field loops has led to a change in local pressure, which causes variations in the flow temperature and velocity.

the behaviour of the magnetic field influences the flow-speed of the upstream medium as the compressed and twisted field lines try to counteract the forces that are being exerted upon them. As a result, the sonic Mach number of the shock changes as well as can be seen in Fig. 4. How this will influence the DSA process is difficult to predict. In general, the presence of large-scale instabilities is beneficial to the the DSA. However, injection process upon which the DSA relies for introducing new supra-thermal particles tends to decrease at lower Mach numbers, as shown

by [12]. Furthermore, the influence of the angle between the magnetic field and the flow is not fully understood. [12] found that at large angles, supra-thermal particles are injected but fail to trigger the upstream instabilities that are required for DSA, similar to results obtained by [6, 7] for high-Mach shocks. On the other hand, [15] found that, given a sufficient particle injection, even quasi-perpendicular shocks can show DSA. However, both models assume a fixed angle between flow and magnetic field, rather than the highly variable one observed here.

#### 4. Conclusions

Although it is possible for a low-Mach, high- $\beta$  shock to accelerate particles to relativistic speeds, which would allow them to contribute to the CR spectrum, the interaction between the charged particles and the magnetic field causes large-scale disturbances in the upstream medium, which, in turn change the nature of the shock. Further research is required to determine whether this will inhibit the injection of new supra-thermal particles.

#### Acknowledgments

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