

# Hybrid Simulations of Particle Acceleration at Shocks

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## Abstract

We present the results of large hybrid (kinetic ions - fluid electrons) simulations of particle acceleration at non-relativistic collisionless shocks. Ion acceleration efficiency and magnetic field amplification are investigated in detail as a function of shock inclination and strength, and compared with predictions of diffusive shock acceleration theory, for shocks with Mach number up to 100. Moreover, we discuss the relative importance of resonant and Bell's instability in the shock precursor, and show that diffusion in the self-generated turbulence can be effectively parametrized as Bohm diffusion in the amplified magnetic field.

**Keywords:** shocks, numerical methods, cosmic rays, supernova remnants, magnetic field amplification

## 1. Introduction

Astrophysical collisionless shocks are usually associated with non-thermal emission, efficient particle acceleration, and magnetic field enhancement. The most prominent examples of non-relativistic collisionless shocks are the blast waves of supernova remnants (SNRs), which are thought to be the sources of Galactic cosmic rays (CRs) up to  $\sim 10^{17}$  eV. Particles are energized by repeatedly scattering across the shock, in a process called *diffusive shock acceleration* [DSA, e.g., 1, 2]. The current carried by energetic ions propagating into the upstream excites plasma instabilities, which lead to the generation of magnetic turbulence. Such amplified magnetic fields enhance the ion scattering, allowing CRs to rapidly gain energy.

The intrinsic non-linearity of this interplay between energetic particles and the electromagnetic fields in the regime of strong amplification cannot be described with analytical techniques, and numerical ones are needed. First-principles kinetic simulations (as particle-in-cell, PIC, simulations) follow both electrons and ions, but are computationally very challenging for realistic mass ratios; they allow the simulation of rather limited physical time and length scales, in units of ion gyration and plasma scales. To overcome this limitation, it is possible

to exploit a *hybrid* technique, which models electrons (assumed massless) as a neutralizing fluid, focusing all the computational dynamical range only on the ion dynamics [see 3, for a review].

In this work, we summarize the main results of recent, state of the art, hybrid simulations with unprecedentedly-large boxes, exploring the space of environmental parameters relevant for SNR blast waves. The crucial questions we address are: i) the efficiency of DSA, and its dependence on shock strength and geometry; ii) the effectiveness of magnetic field amplification in the shock precursor, and the nature of the excited turbulence; iii) the enhancement of particle scattering due to the self-generated turbulence. These three main topics correspond to three papers by Caprioli & Spitkovsky [4, 5, 6], which form a cycle of works aimed to systematically study several aspects of particle acceleration at non-relativistic shocks.

## 2. Acceleration Efficiency

All the simulations are performed with the Newtonian *dHybrid* code [7], and the shock is setup as outlined in [4]. Lengths are measured in units of  $c/\omega_p$ , where  $\omega_p = \sqrt{4\pi ne^2/m}$  is the ion plasma frequency, and time

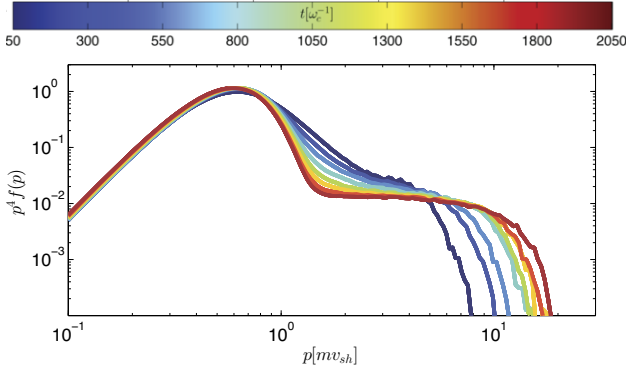


Figure 1: Time evolution of the post-shock ion momentum spectrum for a  $M = 20$  parallel shock, averaged over the whole downstream region. Notice the peak of the thermal (Maxwellian) distribution for  $E \lesssim 2E_{sh}$ , and the non-thermal distribution for  $E \gtrsim 2E_{sh}$ . The spectrum is multiplied by  $p^4$  to emphasize the scaling of the power-law tail, which in perfect agreement with DSA prediction [4].

in units of inverse cyclotron frequency  $\omega_c^{-1} = mc/eB_0$ , with  $c$  the speed of light,  $B_0$  the initial magnetic field, and  $n, e, m$  the ion density, charge, mass; velocities are normalized to the Alfvén speed  $v_A = B_0 / \sqrt{4\pi mn}$ , and energies to  $E_{sh} \equiv mv_{sh}^2/2$ , where  $v_{sh}$  is the velocity of the upstream fluid in the downstream frame. The shock strength is expressed by the Alfvénic Mach number  $M_A \equiv v_{sh}/v_A$ . We assume the sound speed to be comparable to  $v_A$ , and throughout the paper we indicate both the Alfvénic and the sonic Mach numbers simply with  $M$ . The shock inclination is defined by the angle  $\vartheta$  between the shock normal and the background magnetic field  $\vec{B}_0$ , so that  $\vartheta = 0^\circ$  for a parallel shock.

As discussed in [4], for  $p \gtrsim mv_{sh}$  the ion spectrum develops a non-thermal tail, whose extent (corresponding to the maximum energy achieved by accelerated ions) increases with time (see Figure 1). DSA predicts the spectral slope to depend only on the shock compression ratio  $r$  [1, 2]; since  $r \approx 4$  for  $M \gg 1$ , strong shocks are expected to show universal spectra  $\propto p^{-4}$ . The spectrum of non-thermal ions in Figure 1 agrees perfectly with such a prediction. More details, and in particular a discussion of the transition between thermal and non-thermal particles can be found in [4].

Figure 2 shows the acceleration efficiency, expressed as the fraction of the bulk energy flux converted into particles with energy larger than  $\sim 10E_{sh}$ , for shocks with different strengths and inclinations. We outline two important points: i) the acceleration efficiency is  $\gtrsim 10\%$  at strong, quasi parallel shocks. In these cases, the post-shock temperature is reduced with respect to the one derived from the standard Rankine–Hugoniot conditions, the thermal energy being necessarily reduced to

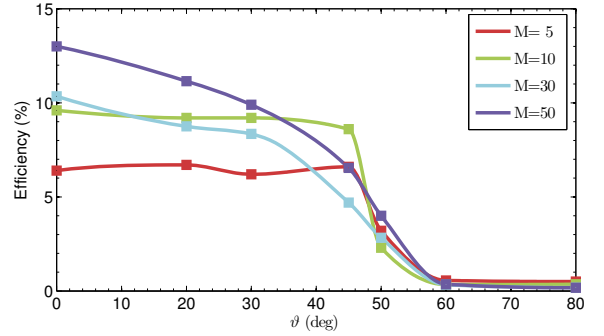


Figure 2: Fraction of the downstream energy density in non-thermal particles at  $t = 200\omega_c^{-1}$ , which represents a good proxy of the saturation value, as a function of shock inclinations and Mach numbers [4]. The largest acceleration efficiency is achieved for strong, parallel shocks, and drops for  $\vartheta \gtrsim 45^\circ$  regardless of the Mach number.

grant energy conservation; ii) the acceleration efficiency drops for  $\vartheta \gtrsim 45^\circ$ , independently of the shock Mach number. At oblique shocks particles are accelerated by a factor of a few in energy because of shock drift acceleration, but they are advected downstream, and eventually thermalized, before being able to enter DSA.

We have shown, for the first time in PIC/hybrid kinetic simulations of strong non-relativistic shocks, that DSA at quasi-parallel shocks produces the expected spectrum of non-thermal ions, typically with an efficiency larger than 10%. Moreover, we proved that injection into DSA is suppressed if the shock is very oblique. These findings, also confirmed in 3D setups, are obtained by using very large computational boxes, in both longitudinal and transverse dimensions, and by choosing very small time steps. In this context, “large” and “small” refer to the dynamics of highest-energy ions in the simulation, whose diffusion length must be encompassed, and whose Larmor gyration must be time-resolved [see 4, for a comparison with the previous literature about hybrid simulations].

### 3. Magnetic Field Amplification

Since the initial formulation of the DSA theory [e.g., 1, 2], particle acceleration has been predicted to be associated with plasma instabilities, and in particular with the generation of magnetic turbulence at scales comparable with the gyroradii of the accelerated particles (resonant streaming instability). More recently, it has been pointed out that some non-resonant, short-wavelength modes may grow faster than resonant ones [non-resonant hybrid, NRH, instability: see 8]. On top of these instabilities, which excite modes parallel to

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