Particle acceleration with super-diffusion

Turbulent super-diffusive shock acceleration

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In Short

- Cosmic rays are accelerated in shocks
- Diffusive shock acceleration is the standard explanation for this acceleration
- Presence of turbulence can lead to super-diffusion of particles
- Super-diffusion is expected to diminish the difference between acceleration efficiencies of parallel and perpendicular shocks
- It is also expected to be more efficient in the case of weak turbulence
- We intend to provide an understanding of this phenomenon using numerical studies

The origin of cosmic rays is one of the most important and interesting topics of scientific research in physics. Cosmic rays are the highest energy particles in the universe and they have a non-thermal origin. The theory of Diffusive Shock Acceleration (DSA) is widely regarded as the mechanism behind acceleration of cosmic rays in supernovae remnant shocks [1]. In this mechanism, fast particles are scattered across a shock front multiple times by the Alfvén waves they themselves generate. At each crossing they gain energy by colliding head-on with their scatterers in a first-order Fermi mechanism, resulting in particle acceleration. This energy gain is balanced by the escape of particles downstream. The transport of particles across the shock front in this case can be modeled as a diffusive process.

There are important differences between the acceleration properties of a parallel shock (where the magnetic field is parallel to the shock normal) and perpendicular shock (where the magnetic field is perpendicular to the shock normal). Particle diffusion is much slower in the field perpendicular direction compared to the parallel direction. This implies that acceleration in perpendicular shocks might be much more effective than acceleration in parallel shocks [2].

This picture ignores the role of pre-existing turbulence near the shock-front. Super-diffusion of particles exists in 3D turbulence. In particular, Richardson diffusion applies in the inertial range of Kolmogorov turbulence [3]. In strong magnetohydrodynamic (MHD) turbulence, the dynamics of magnetic field lines follow the Kolmogorov scaling [4], and thereby are also governed by the Richardson diffusion [5]. Cosmic rays traveling along these lines accordingly are also super-diffusive [6][7]. In our previous project with HLRN we showed that the nature of field line wandering depends on the anisotropy of turbulence, with weak turbulence showing greater correlation lengths in field parallel direction compared to strong turbulence [8].

In ordinary diffusion the average separation between neighboring particles ($\langle \delta x \rangle$) increases with the square root of time $\langle \delta x \rangle \sim t^{0.5}$. For super-diffusion this separation increases faster, $\langle \delta x \rangle \sim t^{\alpha}$ where $\alpha > 0.5$. This super-diffusion will affect the transport of cosmic rays near the shock and affect the acceleration process. It is predicted that due to super-diffusion the acceleration efficiency of parallel shocks will become comparable to the perpendicular shocks, which is different from the expectation of standard DSA mechanism [7]. It is also predicted that weak turbulence may help increase the acceleration efficiency in perpendicular shocks [7].

We intend to study this process numerically. Numerical simulations of DSA have proved to be very challenging due to the extreme nature of the plasma in this system. The shocks required for DSA are extremely supersonic and super-Alfvénic. Moreover, the cosmic rays are ultra-relativistic particles. This introduces multiple length and time scales which are hard to resolve. We intend to use the PLUTO code for this study [9]. PLUTO solves mixed hyperbolic/parabolic systems of partial differential equations (conservation laws) using a variety of finite-difference and finite-volume techniques. It is particularly suitable for high Mach number flows in astrophysical fluid dynamics with shock-capturing. Recently it has also recently introduced a particle module [10]. This has the option of introducing relativistic particles and tracking their trajectory through the Lorentz equation of motion. The advantage of this is that the fast cosmic rays are treated with standard particle-in-cell (PIC) methods while the plasma is treated as a fluid, thus relaxing the constraint to resolve the small particle-scales of the plasma.

We have setup a preliminary simulation which involves a high Mach number standing shock in our simulation domain. This is shown in Fig. 1. The standing shock is located at $x = 0.5$, with the shock normal directed along the x-axis as are the flow velocity and the mean magnetic field. In this we inject turbulence by driving magnetic field fluctuations at the $x = 0$ boundary. These fluctuations advect with the flow and create turbulence throughout the domain. Before crossing the shock (i.e. $x < 0.5$) the fluctuations are weak. After crossing the shock (i.e. $x > 0.5$) these fluctuations get amplified (as seen by the color-scale in Fig. 1)). The particles are injected uniformly in the space between $x = 0.1$ and $x = 0.2$. They have an initial velocity in the x direction, which makes them cross the shock front. A sample of these trajectories are also shown in Fig. 1.

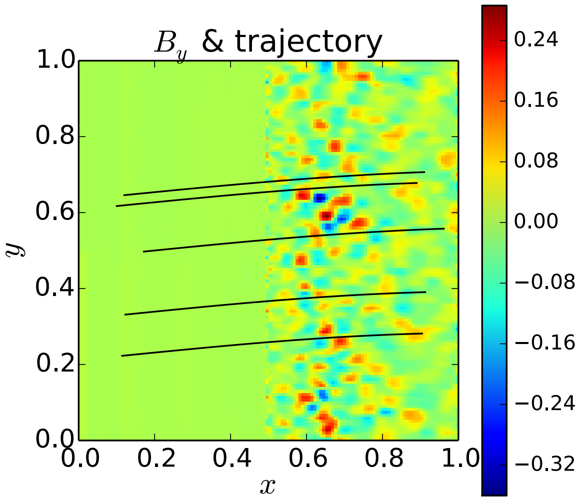

Figure 1: *A sample simulation showing all the three ingredients required in this project - a standing shock at $x = 0.5$, turbulence injected from the $x = 0$ boundary, and particles injected from around $x = 0.1$. The color shows the magnetic field fluctuations while the black lines show a sample of particle trajectories.*

These simulations need to be improved to observe and understand super-diffusive shock acceleration. Particularly, the scales of turbulence have to be set carefully since super-diffusion only exists below the turbulence injection scale. We already have turbulence data from earlier simulations done at HLRN [8] which will be provided at the injection boundary. This turbulence has also been tested to show the super-diffusive characteristics of particle transport by using test particle simulations. Compared to the preliminary simulation above, certainly these simulations will have to be carried out at higher resolutions to resolve the scattering process. Furthermore, a large number of particles will have to be injected in order to get significant statistics of the particle acceleration and their energy spectrum.

The effects of super-diffusion in shock acceleration have only been studied analytically with various approximations [7]. We propose a wide set of simulations which will rigorously test some of this theory and also advance the fundamental understanding of this process. The difference between parallel and perpendicular shocks in the context of super-diffusion is one of the main points to be studied in this project. The role of weak turbulence in this process will also be studied. This study is relevant for high energy astroparticle physics as shock acceleration is the fundamental basis of these high energy cosmic rays.

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More Information

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