Predicting the galactic cosmic ray composition

Charged particle acceleration in collisionless shock waves: Predicting the galactic cosmic ray composition by simulating collisionless shocks

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In Short

- improve the understanding of particle acceleration and cosmic ray generation in non-relativistic shocks
- simulations using a highly parallel hybrid code
- analysis of the influence of the proton/helium admixture on cosmic ray spectra

Introduction High precision spectrometry of galactic cosmic rays (CR) has revealed the lack of our understanding of how different CR elements are extracted from the supernova environments to be further accelerated in their shocks. Most likely, CR are accelerated at collisionless shocks in supernova remnants by diffusive shock acceleration (DSA). By this mechanism, charged particles gain energy by crossing and recrossing the shock front occasionally, while being permanently scattered by magnetic perturbations in the shock vicinity.

The mechanism is physically simple and robust, but some important aspects are still not well understood. One serious difficulty is connected already with its start, when the shock must somehow select a tiny fraction of particles to keep on crossing its front and gaining energy continuously. This initial phase of the DSA is commonly referred to as "injection."

Recent precise measurements of the PAMELA [1] and AMS-02 [2] space-based instruments show a difference between He^{2+} and proton spectra. We argue that the elemental composition of galactic CR might hold the key to their origin. A comparison of injection rates of particles with different mass to charge ratio is a powerful tool for studying the injection process and the DSA in general.

Project Description In this project we aim to further improve the understanding of particle acceleration and cosmic ray generation in non-relativistic shocks by means of numerical modelling. The fully consistent description of intense shock waves structure and evolution in collisionless plasmas belong to the most challenging problems for numerical physics. This is because the most important and interesting phenomena are multiscale and cannot be described fully-hydrodynamically. While the kinetic model is the most fundamental way of descibing a plasma, it suffers from high computational costs, forcing to make use of non-realistic decreased ion-to-electron mass ratios. The hybrid aproach, we use for our simulations, can reduce the computational expense. In this aproach the electron plasma component is treated as a fluid, while for the ion distribution function the kinetic approach is used.

In this project we will perform hybrid simulations of collisionless shocks for realistic shock parameters and the upstream plasma composition with the goal to understand the physical principles by which protons and heavier elements are injected into the DSA at quasi-parallel collisionless shocks. In the simulations the shock is produced by sending a supersonic flow agains a reflecting wall. The interaction between the incoming and reflected streams create a sharp discontinuity, which propagates away from the wall. The initial set-up is similar to that used by D. Caprioli & Spitkovsky [3].

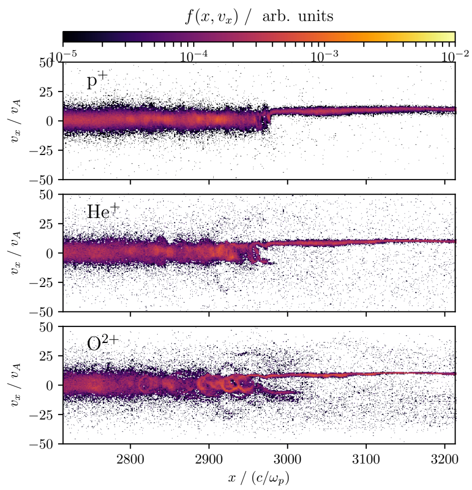

Figure 1: Phase-space $f(x, v_x)$ for different ion species. Only a part of the simulation box centered around the shock transition is shown. The downstream plasma is hot and accelerated particles are present in the downstream as well as in the upstream.

Numerically, we solve the Vlasov equation for the ions using the particle-in-cell (PIC) method, and the motion of the electron fluid is described by the MHD equations. The locality of the PIC methods allows for an efficient parallelisation obtained via a domain decomposition technique: The simulation domain is divided into $N_{sub,x} \times N_{sub,y}$ sub-domains, which are each assigned to a parallel task. Communication is necessary between neighbouring domains to exchange the values of the electromagnetic fields at the boundary positions and the positions and momenta of the macroparticles crossing the borders.

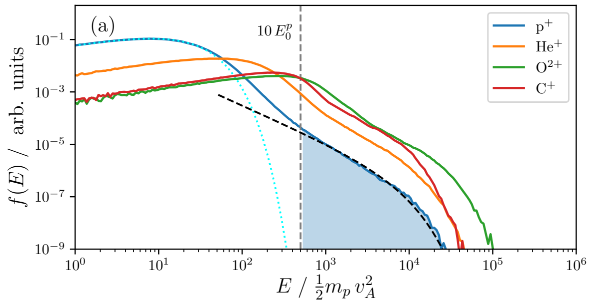

__Figure 2:__ Downstream energy spectra for different ion species for a simulation with a shock velocity v_{sh} = 13 v_A. The spectra consist of a thermal distribution with $T \gg T_0$ and a power-law tail.

Our code shows good strong and weak scaling properties, since the work needed to exchange data is only minor.

In the past we have performed large one-dimensional hybrid simulations focused on the injection of different ion species into the DSA. After the shock has fully developed accelerated ions are clearly visible in phase-space plots (Fig. 1 and energy spectra (Fig. 2) extracted from the simulations. These spectra exhibit a power-law tail, as predicted by the DSA. For the proton energy spectrum (blue line) the thermal distribution (dotted cyan line) and the power-law with cut-off (dashed black line) parts are highlighted.

By performing a series of simulations for different shock velocities and convolving the injection efficiency (which depends on the shock velocity and mass-to-charge ratio of the ion species) with the evolution of a SNR we were able to reproduce the *p*/He ratio measured by AMS-02. The result is presented in Fig. 3. It is clearly visible, that the proton-to-helium ratio is a function of rigidity and the results of our simulations are in good agreement with the experimental data.In particular, our simulations correctly predict the decrease in proton-to-helium ratio with increasing rigidity at exactly the rate measured in the experiments for $\mathcal{R}$>10 GV. In summary, we could show by means of high precision hybrid modelling that the injection is indeed a mass-to-charge dependent process and the results 4 will be published soon.

With the recent release of new data from the AMS-02 spectrometer onboard of the ISS we can now focus also on heavier elements (carbon and oxygen) and compare results of new simulations to the measured spectra, which allows to analyse the mass-to-charge dependence of the injection into the DSA in more detail. Until now our simulations included only one spatial dimension (but all three components of the velocity and fields). In future we want to study particle acceleration and magnetic field amplification in simulations including two spatial dimensions. These simulations are more realistic as additional modes of plasma waves can be present. While in the 1D case waves can only propagate parallel to the shock normal, also transverse propagation is possible in 2D. Special emphasis will be paid to the structure of the shock, as shock corrugation might influence the results, and the correlation between the particle acceleration and magnetic field amplification. In order to unambiguously obtain the structure of the shock waves and the spectra of shock reflected or/and shock accelerated particles, the simulations have to be run for sufficiently long time and in sufficiently large computational boxes. Thus, the progress in this area is directly related to the possibility to access larger resources.

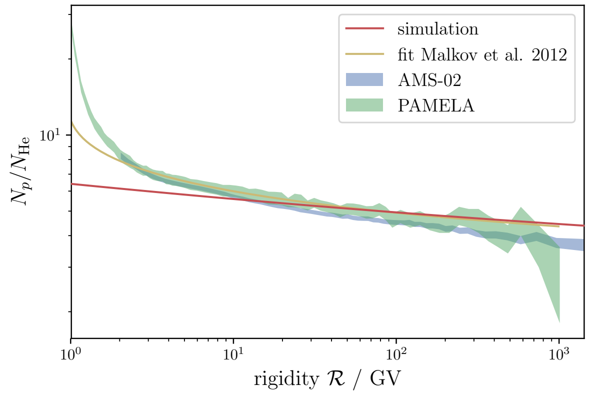

__Figure 3:__ Proton-to-helium ratio as function of rigidity (momentum over charge). The shaded areas denote the PAMELA and AMS-02 measurements with uncertainties. The proton-to-helium ratio extracted from our simulation shows a good agreement at rigidities $\mathcal{R} > 10$ GV.

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https://www.qtmps.physik.uni-rostock.de/

More Information

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Project Partners

M. Malkov, University of San Diego

Funding

DFG Projekt TL 2479/2-1