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

- Non-relativistic collisionless shocks are common in astrophysical environments and proven to be efficient particle accelerators.
- Particle acceleration and thermalization in non-relativistic shocks is not fully understood. Numerical simulations can improve this understanding.
- We perform one- and two-dimensional self-consistent simulations of collisionless shocks using a parallel hybrid code.
- The analysis of the injection dependence on the mass-to-charge ratio of the ions and on the shock velocity allows us to explain the measured cosmic ray spectra.

Introduction. Cosmic rays (CR) have aroused interest since their discovery by Victor Hess in 1912. These particles can reach energies beyond the capability of any man-made accelerator and their energy spectrum follows a power-law dependence over many orders of magnitude. The observations strongly support the hypothesis that galactic cosmic rays are most likely accelerated at collisionless shocks in supernova remnants by diffusive shock acceleration (DSA). The particles gain energy by crossing and recrossing the shock front occasionally, while being permanently scattered by magnetic perturbations in the shock vicinity. While this mechanism is fairly simple, it is not yet fully understood. In particular, the initial process of energetic particle injection into the DSA remains unsolved. Furthermore, the spectra of galactic CR measured with high precision by the space-based detectors PAMELA [1] and AMS-02 [2] show some features, which a complete model of CR acceleration has to explain. Above all, the measurements revealed that the p/He ratio decreases with particle rigidity and that the p/O and p/C ratios are almost identical to that of p/He, see Fig.[1]. Additionally the spectra are found to be steeper than the standard DSA prediction ($\propto E^{-2}$ for strong shocks). Numerical simulations of the plasma in a collisionless shock environment are a powerful tool for understanding the initial phase of particle acceleration and can help to disentangle the processes responsible for features observed in the spectra.

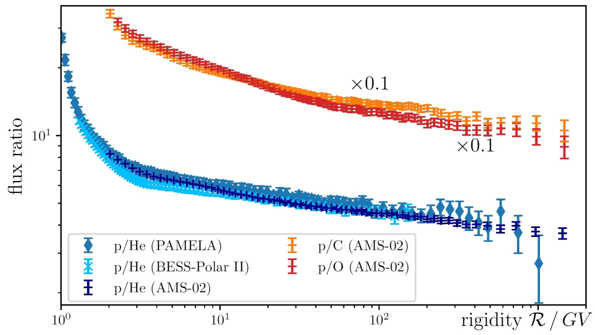

Figure 1: *Proton to helium (carbon, oxygen) ratio as function of rigidity (momentum over charge). In contrast to the prediction by standard DSA the ratio is a function of rigidity.*

Project Description. We aim to further improve the understanding of particle acceleration and cosmic ray generation in non-relativistic shocks by means of numerical modeling. 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 describing a plasma, it suffers from high computational costs, forcing to make use of non-realistic decreased ion-to-electron mass ratios. The hybrid approach can reduce the computational expenses. In this approach the dynamics of the electron plasma component is governed by the MHD equations, while the ion distribution function obeys the Vlasov equation. Numerically, we solve the Vlasov equation using the particle-in-cell (PIC) method. The locality of the PIC method allows for an efficient parallelization obtained via a domain decomposition technique. In the previously granted by HLRN computational period we have performed large 1D and 2D hybrid simulations with up to $\sim 10^8$ particles. Our code shows good strong and weak scaling properties, since the exchange of the data between neighboring domains takes only a minor fraction of the computational time.

In this project we perform hybrid simulations of quasi-parallel collisionless shocks both 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. The particle energy spectra extracted from the simulation show the formation of a power-law tail, which is characteristic for the DSA and extends over several orders of magnitude in energy. We have already systematically investigated (although in a reduced 1D geometry) the injection of different ion species into the DSA and could show that the injection depends on shock velocity and mass-to-charge ratio. By performing a series of simulations for different shock velocities and convolving the injection efficiency obtained from the simulation with the time-evolution of a SNR we were able to reproduce the *p*/He ratio measured by AMS-02. The paper discussing these results is now accepted for the publication in the Astrophysical Journal [3].

However not only the particles accelerated to extremely high energies, but also the low-energy part of the spectrum is of interest. Here the focus lies on the thermalization of the particles upon shock crossing, and especially on the electron to ion temperature ratios in the shocked medium. As the shocks are collisionless an equilibration of ion and electron temperatures might occur only on long timescales. In order to investigate this phenomenon, we have included a test-particle electron population in our hybrid modeling, extracted the temperature ratios T_e/T_i from the simulations and compared our findings with the temperature ratios obtained from observations. The preliminary results are shown on Fig.2. This work is in progress. Using large scale 2D simulations, we

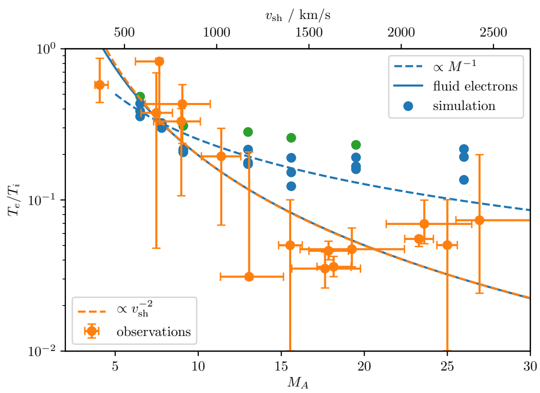

Figure 2: *The temperature ratio T_e/T_i as function of the Mach number obtained from the simulations (blue dots). Additionally the temperature ratio obtained from optical spectroscopy of Balmer dominated shocks [4] together with the inferred scaling behavior are depicted as function of the shock velocity (orange).*

also plan to investigate the influence of a varying angle between the background magnetic field and the shock normal (shock obliquity) on the particle injection and acceleration. For spherically expanding SNR shocks like SN 1006, this angle naturally varies over the shock surface. Since only at quasi-parallel shocks particles are able to return to the upstream, the particle acceleration is only effective in the regions where the shock obliquity is not large. This fact in combination with the evolution of the SNR shock is a possible explanation for the steepening of the energy spectra compared to the DSA prediction. In

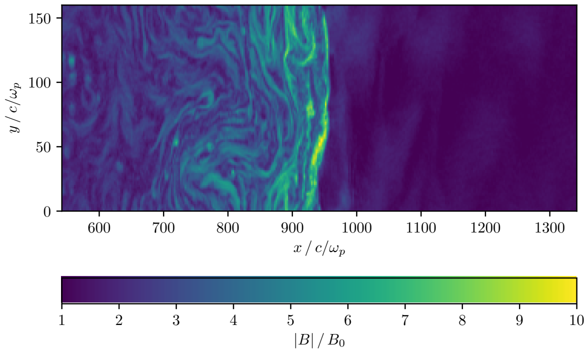

Figure 3: *Magnetic field in the vicinity of the shock transition for a simulation of a quasi-parallel shock (background magnetic field of amplitude B_0 is set parallel to the shock normal). The magnetic field is turbulent and amplified in the downstream. Waves are excited in the upstream and convected by the plasma flow.*

a 2D setup additional wave modes transverse to the shock propagation direction can be generated. The 2D simulations will thus allow for a better description of the wave spectrum, but at the expense of lower particle statistics. Special emphasis has to be paid to the structure of the shock, as shock corrugation might have influence of particle acceleration, 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.

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More Information

[1] O. Adriani et al., *Science* **332**, 69 (2011) doi:10.1126/science.1199172

[2] M. Aguilar et al., *Phys.Rev.Lett.* **115**, 211101 (2015) doi:10.1103/PhysRevLett.115.211101

[3] A. Hanusch et al., *Astrophys.J.* (accepted) (2019), arXiv:1803.00428

[4] P. Ghavamian et al., *Space Science Reviews* **178** (2013) doi:10.1007/s11214-013-9999-0

Project Partners

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