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

- The new generation of detectors reveal features in the cosmic ray spectra that raise doubts regarding the diffusive shock acceleration as a sustainable explanation of the observations.
- The goal of our study is to help to reconcile the predictions of the theory of diffusive shock acceleration with the high-precision measurements of cosmic ray spectra.
- We perform one- and two-dimensional self-consistent simulations of collisionless shocks using a parallel hybrid code.
- We study the influence of minor interstellar medium components to the proton injection into diffusive shock acceleration.

Introduction. Cosmic rays (CRs) have pronounced effects in the galaxy and provide an appreciable fraction of the human radiation doses at the surface of the Earth. Since Viktor Hess' historic balloon ascent in 1911 the problem of CR origin has pondered physicists. In 1934 two astronomers Walter Baade and Fritz Zwicky knitted the extreme astrophysical events, which they named "supernova", with the origin of CRs. The latest direct observations of galactic supernova remnants (SNRs) support a hypothesis that those are the objects where most of the galactic CRs come from. Turning to the leading mechanism of their production, observations favor the diffusive shock acceleration (DSA), a development of the idea proposed by Enrico Fermi in 1949. Modern revolutionary improved observations use the combination of different methods, such as time-of-flight and calorimetric measurements, the deflection of charged particles in a magnetic field, and are able to evaluate the particle spectra with extreme accuracy. For the galactic CRs in the 1 – 500 GeV energy range they have revealed striking deviations from the DSA predictions [1–3]. Such findings challenge the hypothesis of CR origin in SNRs and raise doubts regarding the DSA as a viable explanation of the observed spectra.

Project Description. The interplay between observations, theory and much improved numerical simulations gives further insights into the physics of CRs by disentangling the processes at work. However, as the numerical simulations approach more realistic conditions, their physical understanding becomes more challenging as well.

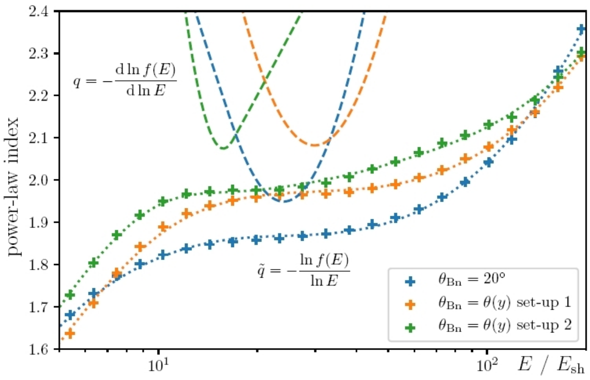

***Figure 1:** Power-law spectral index q calculated from the downstream energy spectra: blue line – $\theta_{\rm Bn}$ = 20° = const., orange and green lines – variable shock obliquity. The discrepancy to the correct asymptotic index q = 1.5 for θ_{Bn} = 20° is due to the limited run time of the simulation and the limited box size. In the region closer to the shock particles are still accelerated to higher energies, and a population of suprathermal particles exist in the transition region between the Maxwellian and the power law.Figure is adapted from [6].*

The interpretation of the present day complicated numerical experiments is not necessarily much easier than that of real observations. Recognizing their limitations by benchmarking between different codes and comparison with simplified physical models is a promising way to understand rapidly improving observations. In our project we aim to further improve the understanding of particle acceleration and CR generation in non-relativistic collisionless shocks by means of numerical modeling.

Hybrid code – The essence of our work consists in the application of advanced computational methods realized in the hybrid code. A principle advantage of the hybrid modeling is the possibility to address the important waves and instabilities on the ion timescale, neglecting the high-frequency modes associated with electrons. Our code was developed and thoroughly tested during the previous computational periods. It employs state-of-art, widely used numerical algorithms and methods. In particular, the particle-in-cell (PIC) method is used to solve the Vlasov equation for the ion plasma components, with the first-order weighting applied to interpolate the fields to the ion positions. The first-order-weighting is also implemented to obtain ion current and charge density from the positions of the ion-particles relative to the grid points. Finally, the Boris pusher is used to propagate ion positions and velocities. The equations of the evolution of the fields are discretized using second-order finite difference stencils.

In the 1D version of the code we use a predictor-corrector method to update the fields. For large 2D simulations we implemented a Barshford-Adams extrapolation for the ion current and a fourth-order Runge-Kutta scheme to advance the magnetic field. Our hybrid algorithms are local and allow for an efficient parallelization via domain decomposition. The current version of the code is suitable for multiple particle species simulations. A dynamical load-balancing keeps the data partition balanced as particles move across different domains. The distribution of numerical data among the processing units and the mutual exchanges are handled by MPI routines. In the previous computational period we have performed large 1D and 2D hybrid simulations with up to $\sim 10^9$ particles.

Simulations – In this project we perform hybrid simulations of collisionless shocks both for realistic shock parameters and 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 characteristic DSA power-law tail, which extends over several orders of magnitude in energy. We have systematically investigated (although in a reduced 1D geometry) the injection of different ion species into the DSA and have shown that the injection depends on shock velocity and mass-to-charge ratio. The followup 2D simulations confirm the 1D findings [4]. By convolving the injection efficiency obtained from the simulation with the time-evolution of a SNR have reproduced the *p*/He ratio measured by AMS-02 [5]. We compared the 1D hybrid simulations of the pure hydrogen plasma and the plasma consisting of two ion species (90% protons and 10% of fully ionized helium). The analysis of the spectrum of the magnetic field in two-ion species plasma proves that if the abundance of He^{2+} component is high, longer waves appear in the spectrum. The critical role of the self-consistent, as opposed to test-particle, treatment of He^{2+} population is confirmed by the enhanced number of downstream protons with high energies. *This work is in progress. In particular, we plan to further investigate (in 2D geometry) the influence of minor interstellar medium components on the proton injection DSA.*

Using large scale 2D simulations, we investigate the influence of a varying angle between the background magnetic field and the shock normal (shock obliquity), see Fig. 2, on the particle injection and acceleration. For spherically expanding SNR shocks like SN 1006, this angle naturally varies over the shock surface. Our simulations have captured a new physical phenomenon in the DSA – the spectrum steepening associated with the variation of shock obliquity along its face. Compared to the case of quasi-parallel shocks, we observe (see Fig.1) the increase of the spectral index by $\Delta q = 0.1 - 0.15$ [6]. While this spectrum steepening may be regarded as relatively small, it is likely to be scalable to longer simulation time, so that larger Δq values can be expected for realistic SNR conditions.

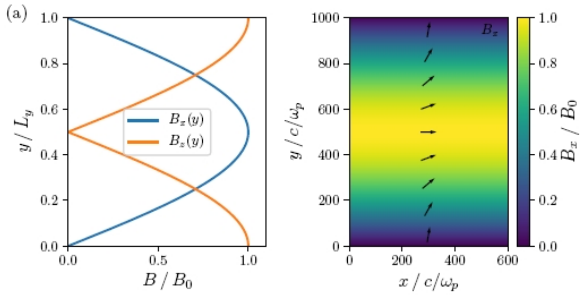

Figure 2: *Initial background magnetic field $\vec{B}_0(y)$ distribution for a configuration with varying shock obliquity. The left panel shows initial dependence of the components B_x and B_z on the transverse coordinate. In the right panel the angle between the shock and the background magnetic field is depicted by the black arrows in addition to $B_x(x, y)$. Figure is adapted from [6].*

In the new computational period we plan to perform hybrid simulations of collisionless shocks with inhomogeneities in the upstream density. They can give insights into the processes that occur at SNR shocks propagating into inhomogeneous or clumpy medium. Large scale MHD simulations of SNR shocks in these environments have already revealed implications for magnetic field amplification [7] and for the CR production efficiency. 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

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Project Partners

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