Mass to charge dependence of particle injection into DSA

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Cosmic Ray (CR) particles are believed to be accelerated in supernova remnant (SNR) shocks via diffusive shock acceleration (DSA). This process is electromagnetic in nature. Particles gain energy while being scattered by converging plasma flows upstream and downstream of a SNR shock. It is still not understood how different CR elements are extracted from the supernova environments and injected into the DSA. Comparing the spectra of accelerated particles with different mass-to-charge ratios is a powerful tool for studying the physics of particle injection. This has become possible only recently due to the high precision spectrometry of galactic cosmic rays [1, 2]. However, the $\Delta q \sim 0.1$ difference in the rigidity spectral indices of protons and helium ions measured by AMS-02 and PAMELA has called into question the leading hypothesis of CR origin at the first place. Several ideas were employed to explain this elemental anomaly, *e.g.*, contribution from different sources with varying p-He mixtures, spallation in the interstellar medium (ISM), or an inhomogeneous p/He ratio in the SNR environment. However, all these theories are either not testable or require additional assumptions. Based on an analytical model the authors of [3] have argued that a specific elemental selectivity of the initial phase of the DSA (injection) occurs in quasi-parallel shocks with no additional assumptions. The similarity of p/He, p/C, and p/O rigidity spectra demonstrated by recent AMS-02 measurements has provided new evidence that injection is indeed a mass-to-charge dependent process.

In oder to investigate the elemental selectivity of the injection mechanism and to determine the injection efficiency of ion species with different mass-to-charge (A/Z) ratio, we performed fully self-consistent hybrid simulations. In these simulations the ions are treated kinetically, while the electrons are considered as a massless, charge neutralizing fluid,

$$n_e m \frac{d\mathbf{v_e}}{dt} = 0 = -e n_e \left(\mathbf{E} + \frac{1}{c}\mathbf{v}_e \times \mathbf{B}\right) - \nabla p_e + e n_e \eta \mathbf{J}, \tag{1}$$

where $-e$, m_e, n_e, and $\mathbf{v}_e$ are the electron charge, mass, density and bulk velocity. The resistivity, η, and pressure, p_e, are assumed to be scalar and an adiabatic equation of state with adiabatic index $\gamma = 5/3$ is used for the electron pressure. All equations are non-relativistic, since we are focusing on the sub-relativistic injection phase. The ion density and current obtained from the simulation particles are used to calculate the fields self-consistently using a predictor-corrector method. All simulations are one-dimensional spatially but with all components of the velocity and the fields included. This reduction in dimension allows to increase the particle statistics and correctly reproduce the wave spectrum and the tails of the distribution function.

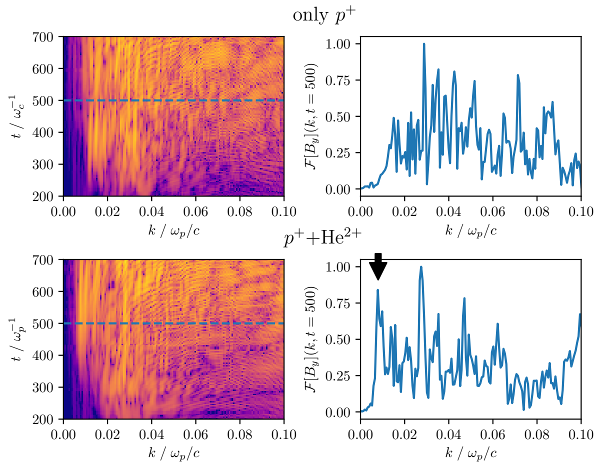

Figure 1: *Spectra of the magnetic field $\mathcal{F}[B_y](k,t)$ for a simulation including only protons (top) and a simulation with 10% of helium ions included (bottom). If He^{2+} is included, a component at lower k is visible in the spectra.*

Lengths are given in units of c/ω_p, with $\omega_p = \sqrt{4\pi n_0 e^2/m_p}$ being the proton plasma frequency, where n_0 is the upstream density and e and m_p are the proton charge and mass, respectively. Time is measured in units of inverse proton gyrofrequency, $\omega_c^{-1} = (eB_0/m_p c)^{-1}$, and velocity in in units of the Alfvén velocity, $v_A = B_0/\sqrt{4\pi n_0 m_p}$. Here B_0 is the magnitude of the background magnetic field.

To initialize the simulations a shock is created by sending a supersonic (and superalfvénic) flow with velocity v_0 against a reflecting wall. Due to the interaction of the emerging counterpropagating beams a shock is formed, which is then propagating parallel to the background magnetic field. We account for the composition of the interstellar medium, by including heavier ions, *e.g.*, helium ions with their respective abundances (10% in number density). Additionally we include carbon and oxygen ions with fractions of $\sim 0.04\%$. Suprathermal ions can drive unstable Alfvén waves in front of the shock. The particle injection and acceleration is controlled by these waves, by regulating the ions access to parts of the phase space which allow repeated

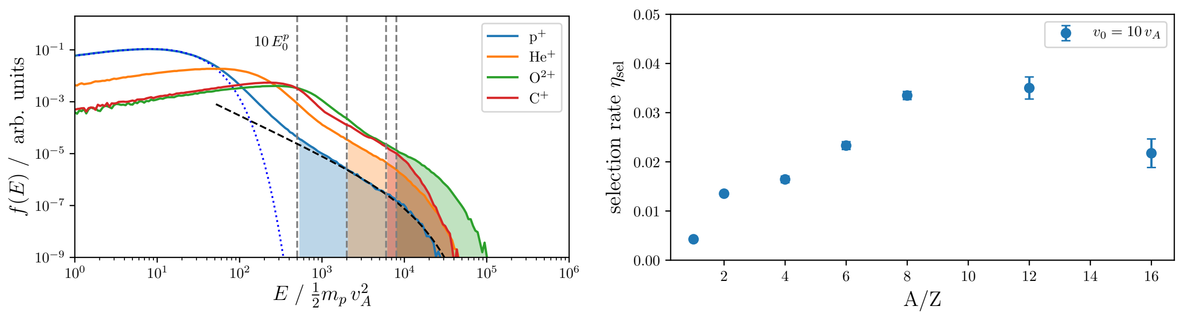

Figure 2: *(left) Downstream energy spectra for a simulation with $v_0 = 10\,v_A$. (right) selection rate as function of mass-to-charge ratio.*

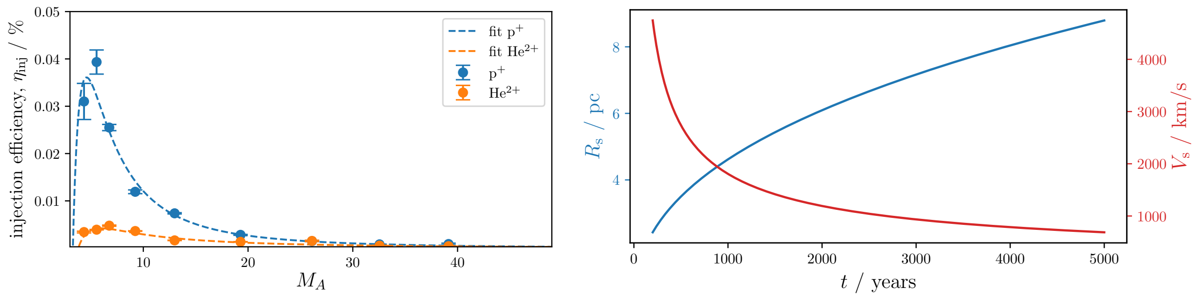

Figure 3: *(left) Injection efficiency of protons and He^{2+} ions obtained from the simulations as function of the shock Mach number. (right) Evolution of the shock velocity and radius during the Sedov-Taylor phase.*

shock crossings. The self-consistent inclusion of helium ions is important to describe the waves generated by them, which have twice the wavelength of the waves created by protons. This influence can be seen clearly in the spectra of the magnetic field in Fig. 1. The black arrow marks a spectral component at low k which is only present if the He^{2+} species is included.

From the simulations we obtain energy spectra of the particles in the downstream for each ion species. These spectra consist of a Maxwellian distribution at lower energies and a power-law tail (see Fig. 2). We find that the tails are well developed for energies $E > 10E_0^\alpha$ with $E_0^\alpha = \frac{1}{2} m_\alpha v_0^2$. We calculate the selection rate, η_{sel}, which corresponds to the fraction of particles in the tail, after the spectra are converged. This selection rate, shown in Fig. 2, is a function of the mass-to-charge ratio. It increases linearly for small A/Z, saturates at $A/Z \simeq 8-12$ in a shock-Mach dependent fashion. The curve in Fig. 2 in contrast to [4] recovers a physically correct asymptotic $A/Z \to \infty$ behavior.

In order to explain the p/He ratio measurements, we need to extract the injection efficiency for protons and helium ions from the simulations [5]. As the transition from the Maxwellian to the power-law is not sharp, this quantity cannot be measured directly. Therefore, we calculate the injection efficiency from the intersection of the Maxwellian and the power-law tail fitted to the energy spectra obtained from the simulation in the following way

$$\eta_{\text{inj}} = \frac{f_{\text{th}}(E_{\text{inj}})}{\int_0^\infty f_{\text{th}}(E)\,\mathrm{d}E}, \tag{2}$$

where E_{inj} is the energy at the intersection of the power-law and Maxwellian fits.

By performing many simulations for different upstream flow velocities, we obtain the injection efficiency as function of the afvénic Mach number (M) and particle species (α). The result is depicted in Fig. 3 (left). It is apparent that proton injection is dominant at low Mach numbers and the maximum is shifted towards higher M for He^{2+} ions. A function $\eta_{\text{inj}}(M) = a(M-b)M^{-c}$ is fitted to the simulation results.

In order to obtain integrated particle spectra, we perform a convolution of $\eta_{\mathrm{inj}}(M)$ with the shock time-dependent $M(t)$ in the range $3.5 < M < 100$, focusing on the Sedov-Taylor phase of SNR evolution. This allows us to extend the spectra to energies far beyond the possibilities of any simulation. The evolution of the shock radius $R_s \propto t^{2/5}$ and velocity $V_s \propto t^{-3/5}$ during the Sedov-Taylor phase is depicted in Fig. 3 (right). The number of ions of CR species α, deposited in the shock interior, during the increase of the shock radius from R_{min} to R_{max}, can be calculated as

$$N_\alpha(p) \propto \int_{R_{\mathrm{min}}}^{R_{\mathrm{max}}} f_\alpha(\mathcal{R}, M(R)) R^2 \, \mathrm{d}R \propto \int_{M_{\mathrm{max}}^{-2}}^{M_{\mathrm{min}}^{-2}} f_\alpha(\mathcal{R}, M) \, \mathrm{d}M^{-2} \tag{3}$$

with $f_\alpha \propto \eta_{\mathrm{inj},\alpha}(M)\,(\mathcal{R}/\mathcal{R}_{\mathrm{inj}})^{-q(M)}$ and $q(M) = 4/(1-M^{-2})$, as predicted by standard DSA theory.

The proton-to-helium ratio as function of rigidity is determined according to Eq. (3) and the result is presented together with the AMS-02 and PAMELA data (shaded areas) in Fig. 4. Our modeling correctly predicts the decrease of the p/He ratio for $\mathcal{R} > 10$ GV with the same rate as measured by the experiments. Only at low rigidities a difference is apparent. Whether this is due to spallation in the ISM or comes from the accelerator(s) remains unclear. Hence, the mass-to-charge dependence of the injection fully explains the measured rigidity dependence of the p/He ratio. Our interpretation of the elemental anomaly is therefore intrinsic to collisionless shock mechanics and does not require additional assumptions, as the contributions from several different SNRs, their inhomogeneous environments or acceleration from grains.

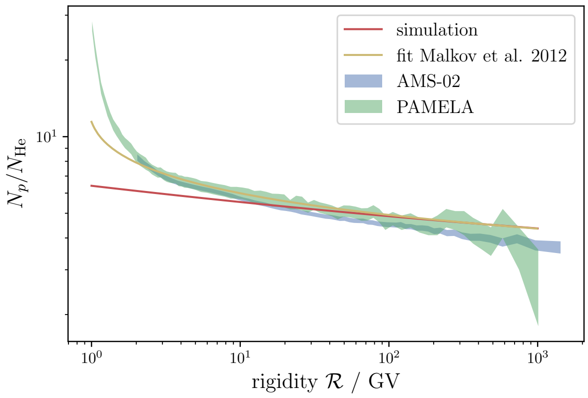

Figure 4: *Proton-to-helium ratio as a function of particle rigidity. Details of the fit are given in [6].*

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