Anomalies in Cosmic Ray Composition: Explanation Based on Mass-to-Charge Ratio

Adrian Hanusch¹, Tatyana Liseykina, Mikhail Malkov²

Introduction

High precision spectroscopy of galactic cosmic rays (CR) has revealed the lack of our understanding of different CR elements are extracted from the supernova remnants (SNR). The electric field, the shock acceleration, and the relativistic jets are important processes that are responsible for the acceleration of CR. However, the similarity of He/Ar, O/C, and Ni/Ar rigidity spectra demonstrated by recent AMS-02 measurements has provided new evidence that injection is a mass-to-charge dependent process. Thus, comparing the spectra of accelerated particles with different mass to charge ratios is a powerful tool for studying the physics of particle injection into the diffuse shock acceleration (DSA).

Anomalies in CR composition

The $\mu$/He ratio as a function of particle rigidity. The plot is adapted from [3] and [4] showing the difference between the rigidity spectral indices of protons and helium. These findings call into question the leading hypothesis CR origin. The CR acceleration mechanism, originally proposed in 1949 by Fermi [3] and actively researched under the name diffuse shock acceleration (DSA), is believed to be self-regulated in nature. Particles gain energy while being scattered by converging plasma flows upstream and downstream of a supernova remnant (SNR).

From the particle equations of motion in terms of their rigidity $\mathcal{R} = p/v^2$, the $\mu$/He ratio $\eta = \eta(\mathcal{R})$ is calculated as

$$\frac{\eta(\mathcal{R})}{\eta_{\text{max}}} = \frac{\mathcal{R}}{\mathcal{R}_{\text{max}}}.$$

It is difficult to see that even a small difference in the rigidity spectral indices of different elements may seriously undermine any electromagnetic acceleration mechanism.

Scenarios

1. contribution from several SNRs with different $\mu$/He mixtures [4] → not testable
2. spallation [5] → not sufficient for explaining the $\mu$/He ratio
3. time-dependence of the shock evolution

(a) SNR environment [6] → not testable
(b) time-dependence of shock strength [7] → testable

Assumption

• mass-to-charge dependence of injection
• power law exponent $\eta(\mathcal{R}) = 4/1 - (M^{2} - 1)$
• shock strength (Mach number $M$) decreases with time
• He is injected more readily at earlier times → harder integrated spectrum

Hybrid Simulation

The dynamics of collisionless shocks can be simulated by means of hybrid simulations. In these simulations the ions are treated kinetically,

$$M \frac{d\nu}{dt} = q E + \frac{v}{m} \times \mathbf{B} - q \mathbf{J},$$

while the electrons are assumed to be a massless, charge-neutralizing fluid,

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}_e + \mathbf{v}, \quad \frac{d\mathbf{v}}{dt} = -\mathbf{E} - \mathbf{v} \times \mathbf{B} + \mathbf{J} \times \mathbf{r}.$$

meaning that in this approach the electron scales are neglected. The electron pressure $p_e$ is assumed to be isotropic with an adiabatic relation between pressure and temperature,

$$p_e = n_e k T_e,$$

where an adiabatic index of $\gamma = 5/3$ is used. In the Maxwell equations the magneto-static (Darmen) model is employed,

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{d\mathbf{B}}{dt}.$$

As in usual particle-in-cell simulations, the ion density and current are extrapolated to a grid using a linear weighting, and serve as sources for the calculation of the fields. The electric field,

$$E = \frac{1}{c} \frac{d\mathbf{B}}{dt} - \nabla \times \mathbf{B} = \mathbf{J} \times \mathbf{r} + \mathbf{J}.$$

is calculated via a predictor-corrector method and is then used for propagating the magnetic field. The simulation dimensions are crucial for the simulation of the shock transition, the cold inflowing stream is visible. The hot downstream plasma is not resolved in the simulation frame.

Magnetic field $B(x,y,z)$ for a simulation with $n_i = 100 \, \text{cm}^{-3}$. Waves excited by the particles are advected towards the shock and compressed downstream.

Injection efficiency

The injection energy $E_{\text{inj}}$ is calculated from the intersection of the Maxwellian and the power-law tail

$$f_{\text{inj}} = \frac{1}{\sqrt{2\pi}} \frac{E_{\text{inj}}}{\sqrt{E}} e^{-E_{\text{inj}}/E}.$$ (6)

The injection efficiency is calculated as

$$\eta_{\text{inj}} = \frac{f_{\text{inj}}(E_{\text{inj}})}{f_{\max}(E_{\text{inj}})}.$$ (7)

in order to model the time-dependent CR acceleration and extract the $\mu$/He ratio, we combine the Mach number dependent injection efficiency with the time dependence of the evolution of a SNR.

Sedov-Taylor phase of the SNR evolution

$$R_{\text{en}} \approx C_2 (E_{\text{inj}})^{1/2}, \quad \frac{V_{\text{sn}}}{C_2} C_2^{-1/2} \approx \frac{2}{3} (E_{\text{inj}})^{1/2}.$$ (10)

Here the spectra are represented in the following way:

$$f_{\text{en}} \approx \eta_{\text{inj}}(E_{\text{en}}/R_{\text{en}}^{1/2})^{2/3}.$$ (12)

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References