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Particle Acceleration in the Heliosphere and in Supernova Remnants

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Abstract. The origin of cosmic rays is one of the key unsolved questions in high-energy astrophysics. It is believed that the bulk of galactic cosmic rays are accelerated in supernova shocks, although this process is not yet fully understood. On the other hand, in the interplanetary medium, non-thermal particles are directly detected in correlation with the presence of shocks. This research aims to develop a one-dimensional numerical model of confinement and acceleration of particles in supernova and heliospheric shocks. We produced PIC-MHD simulations with the injection of cosmic rays already accelerated at the shock position. Our approach can contribute to the understanding of cosmic ray acceleration by testing open questions, such as the development of instabilities and turbulence in the vicinity of shocks, which provides the particles self-confinement.

Resumo. A origem dos raios cósmicos é uma das principais questões não resolvidas na astrofísica de altas energias. Acredita-se que a maior parte dos raios cósmicos galácticos são acelerados em choques de supernovas, embora este processo ainda não seja totalmente compreendido. Por outro lado, no meio interplanetário, partículas não térmicas são detectadas diretamente em correlação com a presença de choques. Esta pesquisa tem como objetivo desenvolver um modelo numérico unidimensional de confinamento e aceleração de partículas em choques de supernovas e da heliosfera. Produzimos simulações PIC-MHD com injeção de raios cósmicos já acelerados na posição de choque. Nossa abordagem pode contribuir para a compreensão da aceleração dos raios cósmicos testando questões em aberto, como o desenvolvimento de instabilidades e turbulências nas proximidades de choques, o que proporciona autoconfinamento às partículas.

Keywords. Acceleration of particles – Cosmic rays – Interplanetary medium – Sun: heliosphere – ISM: supernova remnants

1. Introduction

Cosmic rays are charged particles that permeate astrophysical environments and possess energies much higher than those of particles in thermal equilibrium in these media. Their origin is one of the key unsolved questions in high-energy astrophysics. It is believed that the majority of galactic cosmic rays (with energies up to $\sim$ PeV) are accelerated in shocks produced by the expansion of supernova remnants (SNRs), although this process is not yet fully understood (Longair 2011). On the other hand, in the interplanetary medium, particles accelerated to tens of MeV are directly detected in correlation with the presence of shocks. This research aims to develop a one-dimensional model of confinement and injection of energized particles in the heliosphere and also apply it to supernova shocks.

2. Methods & Procedures

We employ modified magneto-hydrodynamic (MHD) simulations to include the effect of cosmic rays in fully kinetic description, described by macroparticles using the Particle-In-Cell (PIC) technique (e.g. Lebiga, Santos-Lima & Yan 2018). Our PIC-MHD code BUTANTAN solves the following set of equations in one-dimension and Cartesian coordinates:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \tag{1}$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left(\rho \mathbf{v}^{\mathbf{T}} \mathbf{v} - \frac{\mathbf{B}^{\mathbf{T}} \mathbf{B}}{4\pi} + P \right) = -\mathbf{F_{CR}}, \tag{2}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot \left[\left(E + P \right) \mathbf{v} - \frac{(\mathbf{B} \cdot \mathbf{v})\mathbf{B}}{4\pi} \right] = -\mathbf{v} \cdot \mathbf{F_{CR}}, \tag{3}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} \right), \tag{4}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{5}$$

$$\frac{\partial \mathbf{p}_j}{\partial t} = q_j \left(E + \frac{\mathbf{v}_j}{c} \times \mathbf{B} \right), \tag{6}$$

$$\mathbf{F}_{CR} = q_{CR} n_{CR} \mathbf{E} + \frac{1}{c} \mathbf{J}_{CR} \times \mathbf{B}, \tag{7}$$

where ρ, $\mathbf{B}$ and $\mathbf{v}$ represent, respectively, the thermal plasma density, magnetic field strength, and flow velocity. Additionally, E, P and $\mathbf{F_{CR}}$ are the bulk energy density, gas pressure and cosmic ray force, in this order. $\mathbf{p}_j$, q_j and $\mathbf{v}_j$ are, respectively, the momentum, charge and velocity of the particle j and q_{CR}, $\mathbf{J}_{CR}$ and n_{CR} are the charge, current density and number density of cosmic rays, in this order.

This model was first applied to the heliosphere, where we induced the shock propagation as prescribed in Rice & Zank (1999), and initial and boundary conditions were applied as in Rice et al. (2000). Later, we applied it to a supernova remnant, introduced into the system a shock front with injection efficiency of 0.2, a velocity of 1×10^9 $cm.s^{-1}$ and a thermal pressure of 1.8×10^{-12} $erg.cm^{-3}$. Mono-energetic particles with $\gamma = 2$ were injected at the shock position, with an energy power of 20% of the kinetic energy power of compression in the shock frame. Furthermore, in the pre-shock region, the density of the interstellar medium was adopted as 1.64×10^{-24} $g.cm^{-3}$ and the magnetic field was perpendicular to the shock front and with an intensity of 5.0 μG.

3. Results

Figure 1 displays the profiles of radial velocity, and pressure of accelerated particles in the vicinity of the shock front in the heliosphere at two different times. A computational grid resolution of 0.05 AU per grid cell was utilized. It is possible to observe that the structures found in the profiles is similar to the structures presented in both the model in Rice et al. (2000) and in the data obtained by the Voyager 1 and 2 probe also analyzed in Rice et al. (2000).

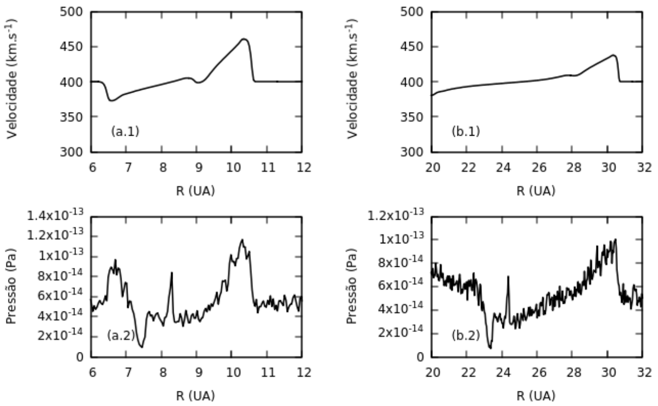

Figure 1. Radial evolution of a shock in the heliosphere with the effects of cosmic rays and the particle injection and acceleration mechanism. Upper panels: radial component of velocity; lower panels: pressure of Galactic cosmic rays and particles accelerated by the shock. We considered Galactic cosmic rays and accelerated protons with energies of 1 GeV and 1 MeV, respectively.

Applying the PIC-MHD model to the conditions of a supernova remnant, we produce Figure 2 which represents the energy density profile of cosmic rays in the domain for four different times. The simulation is carried out in the shock reference frame so it remains centralized in the domain. It is possible to verify that the profiles point to higher energies at the shock position, the point where the particles are injected. Furthermore, in the curves referring to higher times, we observe an increase in energy density on the left side of the shock (pre-shock region), which indicates that the particles are being confined.

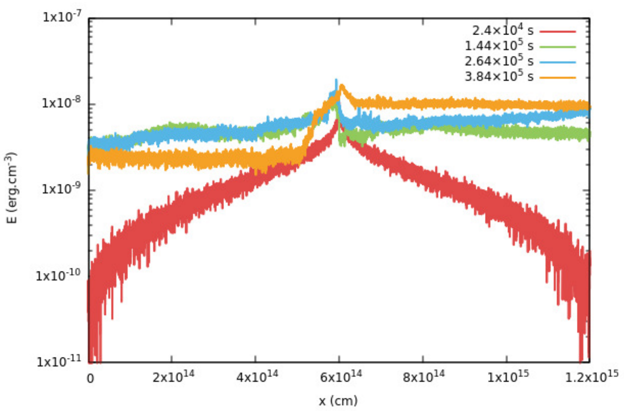

Figure 2. Cosmic ray energy density in the domain for times 2.4×10^4 s in red, 1.44×10^5 s in green, 2.64×10^5 s in blue and 3.84×10^5 s in orange.

Figure 3 shows the energy spectrum of the waves of the medium with $W_b(k) = k|B(k)|^2$, where $|B(k)|^2$ is the power spectrum of the magnetic field. In this graphic, we verify that cosmic rays are capable of exciting waves with wavenumber k of approximately $\frac{1}{r_L}$ and higher values. This happens because the resonant waves depend on the cosine of the particle's pitch angle (μ), following the expression:

$$k = \frac{\omega}{v_{CR}\mu}, \tag{8}$$

where ω is the particle's Larmor frequency given by $\frac{v_{CR}}{r_L}$, thus, for values of $|\mu|$ between 0 and 1, we find the lower limit of k equivalent to $\frac{1}{r_L}$.

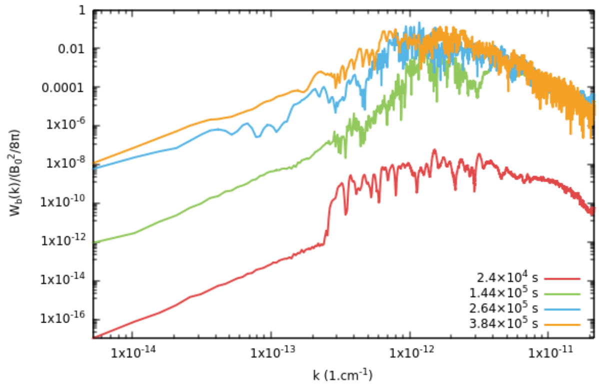

Figure 3. Alfvén waves energy spectrum as a function of k for times 2.4×10^4 s in red, 1.44×10^5 s in green, 2.64×10^5 s in blue and 3.84 $times 10^5$ s in orange.

4. Conclusions & Perspectives

We developed a Particle-In-Cell-MHD one-dimensional numerical simulations to solve the evolution of shocks and energetic particles in the solar wind, in order to compare it with direct observations and previous models based on MHD simulations. We also applied this model to the evolution of cosmic rays in the vicinity of supernova remnant shocks. The results were promising and new simulations of the last scenario with longer duration are being prepared in order to enable the study of accelerated particles in the steady state.

The developing model can contribute to the understanding of the cosmic ray acceleration process, as some open questions, such as the development of instabilities and turbulence near the shock - and their impact on particle confinement - can be tested in the interplanetary medium, where direct observations are available. In the future, we intend to apply it to construct non-thermal emission models of supernova remnants.

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