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Cosmic ray propagation and interactions in the Galaxy

V.N.Zirakashvili

Puskov Institute of Terrestrial Magnetism, Ionosphere and Radiowave Propagation, Russian Academy of Sciences, 142190 Troitsk Moscow, Russia

Abstract

Cosmic ray propagation in the Galaxy is shortly reviewed. In particular we consider the self-consistent models of CR propagation. In these models CR streaming instability driven by CR anisotropy results in the Alfvénic turbulence which in turn determines the scattering and diffusion of particles.

Keywords:
cosmic rays, galactic wind, Galaxy

1. Introduction

Diffusion model of Ginzburg and Syrovatsky [1] was one of the first physically justified models of cosmic ray (CR) propagation. According to this model CR sources are supernova remnants (SNRs) which are situated in the Galactic disk. CR particles perform wandering in the tangled magnetic fields of the Galaxy. The propagation region of CRs is not limited by the Galactic disk but also contains some region above and below the Galactic disk - a so called Galactic halo.

Although CR diffusion was introduced phenomenologically it obtained later the theoretical basis [2]. Diffusive shock acceleration (DSA) [3, 4] in supernova remnants is considered now as a principle mechanism of CR production in the Galaxy. Its main predictions are in accordance with modern gamma-ray observations of supernova remnants [5].

CR confinement time in the Galaxy can be estimated using CR secondaries. CRs contain a significant amount of nuclei that are not abundant in nature. They appear after nuclear fragmentation of primary CRs in the interstellar medium. The measured Boron to Carbon CR ratio is shown in Fig.1 [6]. It is important that the ratio drops when the energy increases. This means that the residence time in the Galactic disk $t_{res}(E)$ is lower for higher energies. It is convenient to use a so called grammage $\Lambda(E) = v\rho t_{res}$ that is the mean amount of matter transversed by CR particles. Here v is the speed of the particles and ρ is the mean gas density in the Galactic disk. The measured secondary to primary ratio can be used to estimate the grammage $\Lambda(E)$. This gives $\Lambda(E) \propto E^{-\mu}$ at energies higher than several GeV per nucleon with the index μ being between 0.3 and 0.6.

In the pure diffusion model the grammage and CR diffusion coefficient are related as $\Lambda(E) \propto D^{-1}$, so we expect that CR diffusion coefficient increases with energy as $D \propto E^{\mu}$. The situation is more complicated in the models which take into account other processes like reacceleration, advection etc.

2. Cosmic ray diffusion in Galactic magnetic fields.

CR diffusion is determined by magnetic inhomogeneities. The scattering of particles occurs via interaction with random magnetic fields δB with the scales comparable with the gyroradius of particles.

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The scattering frequency ν can be estimated as

$$\nu \sim \Omega \frac{\delta B^2}{B^2} \tag{1}$$

Here B is the regular magnetic field and $\Omega = qBv/pc$ is the gyrofrequency of particles with the electric charge q and momentum p. The diffusion coefficient along the regular magnetic field $D_{\|}$ is given by the relation $D_{\|} = v^2/3\nu$.

According to modern theories the MHD turbulence have two main components: anisotropic quasi-Alfvénic incompressible fluctuations with $k^{-5/3}$ spectrum and the isotropic magnetosonic waves with the spectrum $k^{-3/2}$ [7].

The quasi-Alfvénic magnetic inhomogeneities are elongated along the local magnetic field, so when their length is of the order of particle gyroradius the corresponding perpendicular scale is small. That is why the scattering by the quasi-Alfvénic component is not effective [9].

The second isotropic magnetosonic component is good enough for scattering. The corresponding energy dependence of diffusion coefficient $D_{\|} \sim vp^{1/2}$ is in good agreement with measured secondary to primary ratios of Galactic CRs. This possibility is considered as a good physical solution for the propagation problem [8].

However the magnetosonic component exists only when MHD approximation of interstellar turbulence is used. Magnetosonic waves are damped via the linear Landau damping [10] in the more justified plasma description of interstellar turbulence. This damping prevents nonlinear energy transfer of energy to smaller scales for magnetosonic waves. The Landau damping is weaker for waves propagating at small angles relative to the magnetic field. However this does not help because the rate of nonlinear transfer of energy to small scales is also weaker at these angles. So only strongly oblique magnetosonic waves with their high phase velocities can avoid the damping and can transfer the energy to smaller and smaller scales. But their obliqueness again will result in the inefficient scattering of CR particles.

We conclude that the main components of interstellar turbulence can not provide the scattering of the main part of Galactic CRs with energies below 1 PeV. For higher energies gyroradius of particles is above 0.1 pc and these particles in principle can be scattered by the background turbulence.

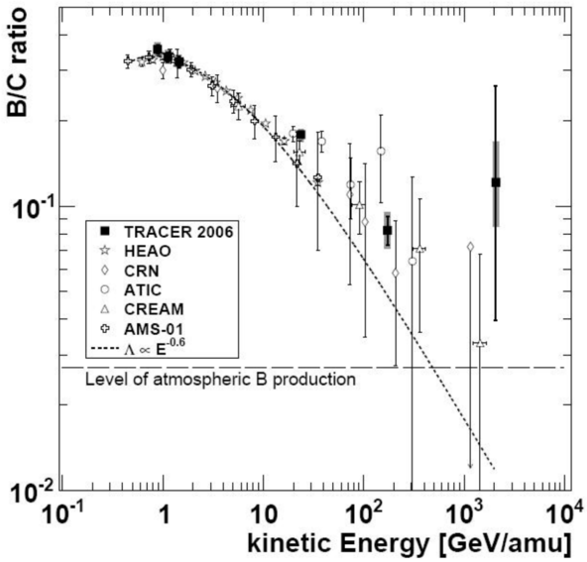

Figure 1: Measurements of B/C ratio performed in different experiments [6].

3. Cosmic ray streaming instability and damping of waves

In this regard another sources of magnetic turbulence should be considered. The best candidate is a so called streaming instability driven by anisotropic CR distribution. Its importance for CR propagation was recognized many decades ago [12, 13, 14, 15, 16]. The growth rate of unstable Alfén waves is given by the equation [17]

$$\Gamma_{CR} \sim \Omega_i \frac{N(r_g > k^{-1})}{n} \left(\frac{u_{cr}}{v_A} - 1 \right). \tag{2}$$

Here Ω_i is the gyrofrequency of thermal ions, n is the plasma number density and $N(r_g > k^{-1})$ is the number density of CR particles with gyroradii $r_g = pc/qB$ higher than the inverse wavenumber k. The instability develops when the mean velocity of CR distribution u_{cr} is higher than the Alfvén velocity v_A.

CR streaming produces waves with the scale k^{-1} comparable with the gyroradius of particles. The particles in turn are scattered by these waves.

Alfvén waves produced by GeV particles have the growth rate $\Gamma \sim 10^{-10}$ s^{-1}. So the growth time is only 300 years that is this time is very short in comparison with other Galactic time scales.