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Cosmic ray propagation in the interstellar medium

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Abstract. We briefly review the theoretical aspects of cosmic ray transport in the Galaxy. A special attention is paid to the diffusion model of cosmic ray propagation.

Key words. cosmic rays – interstellar medium – magnetic fields

1. Introduction

The origin of relativistic particles is associated with the most energetic astronomical objects in the Galaxy, primarily with supernovae. After leaving the sources, the charged energetic particles diffuse in random magnetic fields that accounts for their high isotropy and relatively long confinement time in the Galaxy. The galactic diffusion model explains the data on particle energy spectra, composition, and anisotropy. It also provides a basis for the interpretation of radio-astronomical, X-ray and gamma-ray measurements.

2. Basic diffusion model

The basic model for the investigation of cosmic-ray propagation in the Galaxy is the flat halo diffusion model (Ginzburg & Ptuskin 1976; Berezinsky et al. 1990). It has simple geometry which reflects, however, the most essential features of the real system. It is assumed that in the model with a static cosmic-ray halo (i.e. without galactic wind flow) the region of cosmic ray diffusion in the Galaxy has the shape of a cylinder with a radius $R(\sim 20$ kpc) and a total height $2H(H \approx 4$ kpc), see Figure 1. The cosmic-ray sources are distributed within an inner disk having characteristic thickness $2h(\sim 300$ pc). Hundreds of stable and radioactive isotopes should be included in the calculations of nuclear fragmentation and transformation of energetic nuclei in the course of their interaction with interstellar gas. The analytical and semi-analytical models (Berezinsky et al. 1990; Jones et al. 2001; Shibata et al. 2004; Maurin et al. 2010), were employed for investigations of different aspects of cosmic ray propagation in the Galaxy. The most comprehensive full-scale modelling of cosmic ray transport in the entire Galaxy and for all cosmic-ray species can be done only through the numerical modelling. The most advanced code developed for the numerical calculations of cosmic ray propagation is the Galactic Propagation (GALPROP) code which uses a Crank-Nicholson implicit second-order scheme (Strong & Moskalenko 1998; Strong, Moskalenko & Ptuskin 2007; Vladimirov et al. 2011; Trotta et al. 2011). It incorporates as much realistic astrophysical input as possible together with latest theoretical

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development and numerically solves transport diffusion-convection equations for all cosmic-ray species. The code was created to enable simultaneous predictions of all relevant observations, including cosmic ray nuclei, electrons, positrons and antiprotons; gamma-rays; and synchrotron radiation.

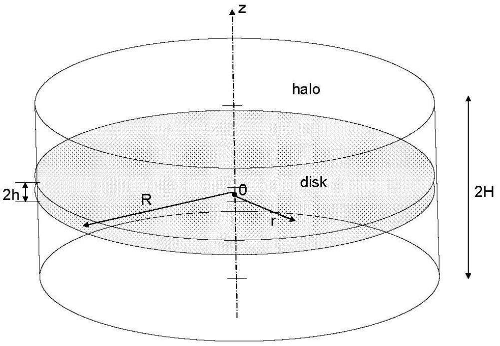

Fig. 1. The region of cosmic ray propagation in the Galaxy. The cosmic ray sources and the interstellar gas are mainly distributed in the thin disk with characteristic half thickness much smaller than the height of cosmic-ray halo, $h \ll H$.

One of the major channels of information about cosmic-ray propagation is the abundance of secondary energetic nuclei produced as the result of spallation of more heavy primary nuclei interacting with the interstellar gas. The observed ratio of fluxes of secondary to primary nuclei, for example the Boron to Carbon ratio, is decreasing with energy at $E > 1$ GeV/nucleon that is naturally explained by the increase of the diffusion coefficient with magnetic rigidity $D \propto vR^a$ (here v is the particle velocity, $R = pc/Ze$ is the particle magnetic rigidity). The index $a \approx 0.5 - 0.6$ was found in the plain diffusion model, and $a \approx 0.3$ was determined in the diffusion model with cosmic ray distributed reacceleration by the interstellar turbulence. The leakage time of cosmic rays from the Galaxy decreases correspondingly. It does not refer to energies below ~ 1 GeV/n where the rising with energy ratio of fluxes of secondary to primary nuclei is observed. Several versions of the basic diffusion model were considered in an attempt to determine which may explain the peak in secondary to primary ratio at ~ 1 GeV/n. The most probable physical explanations are discussed below in Section 3.

Antiprotons also represent secondary species produced by cosmic rays via interaction with atomic nuclei in the interstellar gas, see Adriani et al. (2009) for recent experimental results and discussion. For a long time, the cosmic ray positrons were considered as pure secondaries. However, the rise of the $e^+/(e^- + e^+)$ ratio observed at energies $5 - 100$ GeV (Adriani et al. 2009a) proved the presence of primary positrons. Pulsars and pulsar wind nebulae are considered as their most probable sources (Hooper, Blasi & Serpico 2008). The comprehensive review of the problem can be found in Grasso et al. (2009).

3. Nature of cosmic ray diffusion

The theory of energetic particle transport in galactic magnetic fields is constructed in much the same way as in the well studied case of particle transport in the interplanetary magnetic fields, see Toptygin (1985); Berezinsky et al. (1990); Schlickeiser (2002).

The random component of interstellar magnetic field with an extended spectrum of inhomogeneities can provide the resonant particle scattering and spatial diffusion of cosmic rays. The diffusion coefficient can be estimated as $D \approx (vr_g/3) \times (B^2/B^2_{res})$, where B_{res} is the amplitude of the magnetic field at the resonant $k_{\|,res} = 1/r_g$ ($k_{\|,res}$ is the component of the wave vector parallel to the direction of the local magnetic field, $r_g = pc/ZeB$ is the Larmor radius of particle which has charge Ze and momentum p). Actually, the diffusion is anisotropic locally and directed predominantly along the magnetic field but the large scale wandering of magnetic field lines makes diffusion close to isotropic on scales larger than ~ 100 pc.

The information about the interstellar turbulence spectrum has been obtained from radio scintillation and refraction observations (sensitive to fluctuations of thermal electron density), measurements of the differential Faraday rotation angles from distant sources (mainly produced by fluctuations in the interstellar magnetic field), and the observations of random motions in the interstellar gas. These data are consistent with the assumption that a single close-to-Kolmogorov spectrum extends from scales 10^8 to 3×10^{20} cm, see Armstrong, Rickett & Spangler (1995) and references therein. The Kolmogorov spectrum is of the form $W(k) \propto k^{-5/3}$. Other types of spectra frequently used to describe the interstellar turbulence are $W(k) \propto k^{-2}$ for the shock-dominated turbulence, see e.g. the model of Bykov & Toptygin (1987), and the spectrum $W(k) \propto k^{-3/2}$ derived by Iroshnikov (1963) and Kraichnan (1965) in the phenomenological theory of MHD turbulence. Comprehensive reviews of MHD turbulence with application to the interstellar conditions have been given by Elmegreen & Scalo (2004); Scalo & Elmegreen (2004).

The estimate based on the empirical value of the diffusion coefficient $D \approx 3 \times 10^{28}$ cm^2/s for GeV particles requires the level of turbulence at the principal scale $k_{\mathrm{L}} = 10^{-21}$ cm^{-1} of the order $\delta B_{\mathrm{tot}}/B \sim 0.2$ for an Iroshnikov-Kraichnan spectrum $W(k) \propto k^{-3/2}$ ($a = 1/2$) and $\delta B_{\mathrm{tot}}/B \sim 1$ for a Kolmogorov-type spectrum $W(k) \propto k^{-5/3}$ ($a = 1/3$). At the same time, the data on Faraday rotation angles favor the Kolmogorov spectrum with $\delta B_{\mathrm{tot}}/B \sim 1$ and $k_{\mathrm{L}} = 10^{-21}$ cm^{-1}.

It must be emphasized that the theoretical description of MHD turbulence is a complicated and not completely solved problem even in the case of small-amplitude random fields. Goldreich & Sridhar (1995) exploited anisotropy in MHD turbulence and obtained Kolmogorov-like spectrum for the energy density of Alfvén waves. The main part of the energy density in this turbulence is concentrated perpendicular to the local magnetic field wave vectors $k_\perp \approx k$, while the parallel wave numbers are small: $k_\parallel \sim \left[kW(k)/\left(B_0^2/4\pi\right)\right]^{1/2} k_\perp$. This turbulence does not significantly scatter cosmic rays (Bereznyak, Yan & Lazarian 2011). The distribution of slow magnetosonic waves passively follows that of Alfvén waves. They are probably responsible for the observed interstellar electron density fluctuations. The fast magnetosonic waves with the Iroshnikov - Kraichnan spectrum $W(k) \propto k^{-3/2}$ may have an independent nonlinear cascade which is isotropic and can efficiently scatter cosmic rays. These conclusions were supported by numerical simulations of Cho & Lazarian (2002). This concept of the MHD turbulence favors the scenarios where cosmic rays are scattered by fast magnetosonic waves with the Iroshnikov-Kraichnan spectrum.

4. Spectrum of Galactic cosmic rays

The knowledge of the diffusion coefficient is absolutely essential for understanding the nature of the spectrum of galactic cosmic rays that is determined by the processes of acceleration in the sources (supernova remnants) and propagation in galactic magnetic fields. The two specific asymptotic power laws of the diffusion coefficient $D \propto (p/Z)^{1/3}$ and $D \propto (p/Z)^{1/2}$ at very high energies together with the observed spectrum approximated by the power law $J \propto E^{-2.7}$ imply the cosmic ray source spectra close to $q \propto E^{-2.2}$ and $q \propto E^{-2.4}$ respectively.

The contemporary modelling of cosmic ray production by supernova remnants was made by Ptuskin, Zirakashvili & Seo (2010). The spectra of high-energy protons and nuclei accelerated by supernova remnant shocks were calculated taking into account magnetic field amplification and Alfvénic drift both upstream and downstream of the shock for different types of supernova remnants during their evolution. The action of cosmic ray pressure on the shock structure was taken into account. Four different types of supernova remnants (Ia, Ib/c, IIP and IIb) with corresponding burst rates were included in the calculations. It was found that the maximum energy of accelerated particles may reach 5×10^{18} eV for Fe ions in Type IIb supernova remnants. The steady state spectrum of cosmic rays produced in the Galaxy was calculated with the deduced source spectra of protons and different kind of nuclei up to Iron. The diffusion coefficient with a high energy asymptotics $D \propto (p/Z)^{0.54}$ as determined by Jones et al. (2001) from the accurate fit to B/C data was used in the calculations. The derived energy spectrum of cosmic rays including the knee structure around 4×10^{15} eV is in good agreement with the spectrum measured at the Earth up to about 5×10^{18} eV. This result is strongly in favor of cosmic ray galactic diffusion on the MHD turbulence with the spectrum close to $k^{-3/2}$. The Kolmogorov type spectrum $k^{-5/3}$ is unlikely.

The described model of cosmic ray production in supernova remnants has potential for explanation of the fine structure of cosmic ray spectrum above the knee (Arteaga-Velrazquez 2010; Berezhnev et al. 2011) that probably reflects the contribution of different types of supernova remnants and the different types of nuclei to the observed spectrum. Also, a nearby supernova remnant may produce some small features (peaks) in the cosmic ray spectrum between 10^{16} and 10^{17} eV (Erlykin & Wolfendale 1997).

5. Cosmic rays in a self-consistent model of Galactic wind

The galactic cosmic rays are not always treated as test particles moving in given magnetic fields. The energy density of cosmic rays estimated as $w_{cr} \sim 1$ eV/cm^3 is approximately equal to the energy density of magnetic field and to the energy density of turbulent motions of the interstellar gas. The presence of nonthermal component in the interstellar medium leads to the collective (plasma) effects and in particular to the cosmic ray streaming instability. The cosmic ray streaming instability of magnetohydrodynamic waves, which develops when the bulk velocity of cosmic rays exceeds Alfven velocity, is the most important, see Wentzel (1974); Berezinsky et al. (1990); Kulsrud (2005) and references therein.

Plasma effects make the overall picture of cosmic ray diffusion in the Galaxy more complicated than it was discussed in Section 3. In principle, the cosmic ray diffusion coefficient should be calculated selfconsistently with the account taken for the generation of turbulence by streaming cosmic rays. The examples of such approach and the corresponding transport equations can be found in the works of Skilling (1975) and Ptuskin, Zirakashvili & Plesser (2008). The necessity of considering the variety of dissipation processes of linear and nonlinear wave dissipation in the interstellar medium adds complexity to the investigation and makes the results strongly dependent on the interstellar gas parameters: the density, the state of ionization, the temperature.

In addition to kinetic effects, the cosmic rays may induce significant hydrodynamic effects in the Galaxy. Accounting for cosmic ray pressure is principally important for the formation of a halo filled with gas, magnetic field, and relativistic particles. The equilibrium distribution of the interstellar medium above the galactic plane in the gravitational field of stars is subject to the Parker instability (Parker 1966). Cosmic rays play a significant role in the development of this instability. The instability gives rise to large-scale turbulence and helps sustain an almost equipartition energy distribution among cosmic rays, magnetic fields, and turbulent gas motions. The characteristic time for instability development is $\sim 10^7$ years in the gaseous galactic disk, and $\sim 10^8$ years in the gas halo.

It is possible that the gas in the galactic halo is not in static equilibrium but is involved in large-scale convective motion - the galactic wind. The data on galactic soft X-ray emission suggest that a wind exists in our Galaxy, see Everett et al. (2007). It can be supported by cosmic ray pressure (Breitschwerdt, McKenzie & Voelk 1991). A model was constructed by Zirakashvili et al. (1996) where cosmic rays, after leaving the sources (the supernova remnants), determine the wind outflow in the rotating Galaxy with a frozen magnetic field. Here, the streaming instability of cosmic rays exiting the Galaxy along the spiral magnetic field lines leads to the MHD turbulence generation, that self-consistently determines the diffusion-convection transport of relativistic particles. The level of turbulence is regulated by the nonlinear Landau damping on thermal ions. The outflow velocity reaches ~ 400 km s^{-1} at the distance of several hundred kpc away. The external pressure of the intergalactic gas produces a termination shock at the distance of

~ 300 kpc. In this model, the diffusion coefficient of cosmic ray is not given independently and is self-consistently calculated, being dependent on the power of sources and the spectrum of accelerated particles (Ptuskin et al. 1997). Remarkably, the obtained transport coefficients and other parameters are consistent with the empirical diffusion-convection model (Bloemen et al. 1993) for cosmic ray propagation in the Galaxy with galactic wind.

6. Conclusions

The diffusion model provides reasonably good description of cosmic ray propagation in the Galaxy even under simplified assumptions on the cosmic ray transport coefficients and the geometry of propagation region.

The cosmic ray origin scenario where supernova remnants serve as principle accelerators of cosmic rays in the Galaxy is strongly confirmed by recent numerical simulations. Supernova remnants can provide cosmic ray acceleration up to 5×10^{18} eV.

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