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Propagation of galactic cosmic rays

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ABSTRACT

The theoretical aspects of cosmic ray transport in the Galaxy are discussed. The emphasis is on the diffusion model of cosmic ray propagation. The results of the empirical modelling are combined with the approach based on the kinetic theory of particle interaction with random magnetic fields. The plasma effects of cosmic rays in the interstellar medium are briefly discussed.

1. Introduction

The major part of observed at the Earth cosmic rays is produced in Galactic sources. The origin of relativistic particles is associated with the most energetic astronomical objects primarily with supernovae and their products – supernova remnants and pulsars. The spectra of cosmic rays are shaped by two basic processes – the acceleration in the sources and the subsequent propagation in the interstellar medium. Upon 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 since the non-thermal continuous radiation in space is produced by the energetic charged particles – electrons, protons, and nuclei. The diffusion approximation probably works for particles with energies not much larger than $10^{17}Z$ eV (Z is the particle charge). The trajectory calculations in galactic magnetic field are employed to study cosmic ray propagation at higher energies.

2. Empirical diffusion model

The procedure of the modelling of cosmic ray propagation in the Galaxy can be summarized in the following way. One must first specify the cosmic ray sources, define the shape of the cosmic ray halo and the conditions at its boundaries. The basic diffusion–convection equations for different cosmic ray species should incorporate possible energy loss and gain processes in the interstellar medium, nuclear fragmentation, and radioactive decay of unstable nuclei. One can then calculate the distribution functions of protons and the different types of nuclei. The empirical transport coefficients of cosmic rays (diffusion coefficient and convection velocity), the properties of cosmic ray sources (total power, energy spectra of different components, elemental and isotopic composition), and the size of confinement region of cosmic rays in the Galaxy can be found from the fit to all available data on cosmic rays.

The cosmic ray transport equation for a particular particle species can be written in the general form, see [1]:

$$\frac{\partial F(\mathbf{r},p,t)}{\partial t} - \nabla(\mathbf{D}_{xx}\nabla F) + \nabla(\mathbf{u}F) - \frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial}{\partial p}\frac{F}{p^2}\right) + \frac{\partial}{\partial p}\left[\dot{p}F - \frac{p}{3}(\nabla\mathbf{u})F\right] + \frac{F}{\tau_f} + \frac{F}{\tau_d} = q(\mathbf{r},p,t), \quad (1)$$

where $F(\mathbf{r},p,t)$ is the cosmic ray density per unit of total particle momentum p at position $\mathbf{r}$, $F(p)dp = 4\pi p^2 f(\mathbf{p})dp$ in terms of phase-space density $f(\mathbf{p})$; $q(\mathbf{r},p,t)$ is the source term including primary, spallation, and decay contributions; primaries may be produced by the distribution of cosmic ray sources discrete in space and time, $\mathbf{D}_{xx}$ is the spatial diffusion tensor (the notation D will be used for the isotropic scalar diffusion coefficient); $\mathbf{u}$ is the convection velocity; diffusive reacceleration by the interstellar turbulence is described as diffusion in momentum space and is determined by the coefficient D_{pp}; $\dot{p} \equiv dp/dt$ is the momentum gain or loss rate; τ_f is the timescale for loss by fragmentation; and τ_d is the timescale for radioactive decay. The spallation part of q depends on all progenitor species and their energy-dependent cross sections, and the gas density $n(\mathbf{r})$. In general, it is assumed that the spallation products have the same kinetic energy per nucleon as the progenitor. K-electron capture and electron stripping can be included via τ_f and q. $\mathbf{D}_{xx}$ is, in general, a function of $(\mathbf{r}, \beta, p/Z)$, where $\beta = v/c$, Z is the charge, and p/Z determines the gyroradius $r_g = pc/ZeB$ in a given magnetic field $\mathbf{B}$. $\mathbf{u}(\mathbf{r})$ is the large-scale convection velocity or the galactic wind velocity. The term in $\nabla\mathbf{u}$ represents adiabatic momentum gain or loss in the

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nonuniform flow of gas, with a frozen-in magnetic field whose inhomogeneities scatter the cosmic rays. τ_f depends on the total spallation cross section and $n(\mathbf{r})$. $n(\mathbf{r})$ can be based on surveys of atomic and molecular gas, but can also incorporate small-scale variations such as the region of low gas density surrounding the Sun. This equation treats continuous momentum loss only. Catastrophic losses can be included via τ_f and q. Cosmic ray electron, positron, and antiproton propagation constitute special cases of this equation, differing only in their energy losses and production rates. The boundary conditions depend on the model. Usually, $F = 0$ is assumed at the halo boundary, where particles escape into intergalactic space.

The basic model for the investigation of cosmic-ray propagation in the Galaxy is the flat halo diffusion model [1–3]. The model has simple geometry which reflects, however, the most essential features of the real system. It is assumed that the system has the shape of a cylinder with a radius $R \approx 20$ kpc and a total height $2H$ ($H \approx 4$ kpc), see Fig. 1. The cosmic-ray sources are distributed within an inner relatively thin galactic disk having characteristic thickness $2h \approx 300$ 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 electron–positron component and the energetic antiprotons, which are produced in a course of cosmic-ray propagation are also incorporated in the calculation procedure.

The analytical and semi-analytical models, e.g. [3–6], were employed for investigations of different aspects of cosmic ray propagation in the Galaxy. The most comprehensive full-scale modelling of the diffusion 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 [1,7–9]. It incorporates as much realistic astrophysical input as possible together with latest theoretical 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.

It is remarkable that the model with simple assumptions about the geometry of the propagation region (a cylinder with absorbing boundaries) and the independent on coordinates diffusion coefficient successfully describes a great body of data on cosmic rays and nonthermal radiation in the Galaxy [1]. The point that is not clarified yet is the radial distribution of cosmic ray sources in the Galaxy. The interpretation of data on diffuse gamma-ray emission requires constant spatial distribution of cosmic ray sources beyond the Solar Circle that is in contradiction with the distribution of supernova remnants [10].

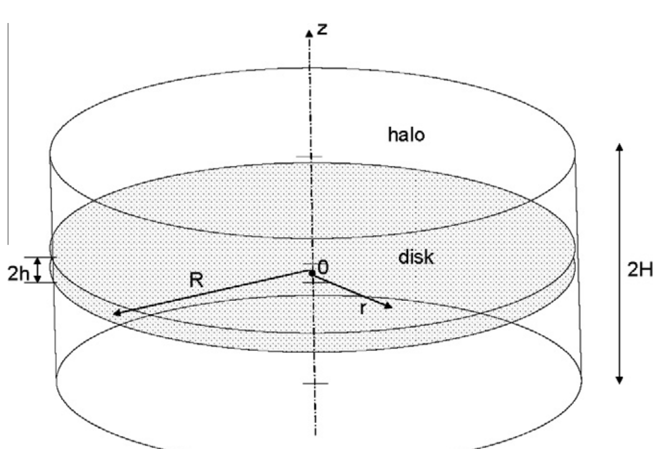

Fig. 1. The region of cosmic ray propagation in the Galaxy. The cosmic ray sources and the interstellar gas are mainly distributed in the thin disk with characteristic half thickness much smaller than the height of cosmic-ray halo, $h \ll H$.

One of the major channels of information about cosmic-ray propagation is the abundance of secondary energetic nuclei, Li, Be, B, Sc, V, Ti, ^{2}H, ^{3}He and others, 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, e.g. [11,12].

Antiprotons also represent secondary species produced by cosmic rays via interaction with atomic nuclei in the interstellar gas, see [13] 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 [14] proved the presence of primary positrons. Pulsars and pulsar wind nebulae are considered as their most probable sources [15]. The comprehensive review of the problem can be found in [16].

The basic version of the propagation model, the GALPROP plain diffusion model, has no reacceleration, $D_{pp} = 0$, and large-scale convection, $u = 0$. It is characterized by the following set of parameters mainly derived from the observations of primary and secondary nuclei [17]:

$$\begin{aligned} &D = 2.2 \times 10^{28} \beta^{-2}\ \mathrm{cm^2/s} \quad \text{at } R \leqslant 3\ \mathrm{GV}, \\ &D = 2.2 \times 10^{28} \beta^{-2} (R/3\ \mathrm{GV})^{0.6}\ \mathrm{cm^2/s} \quad \text{at } R > 3\ \mathrm{GV}, \\ &q \propto (R/40\ \mathrm{GV})^{-2.3} \quad \text{at } R \leqslant 40\ \mathrm{GV}, \\ &q \propto (R/40\ \mathrm{GV})^{-2.15} \quad \text{at } R > 40\ \mathrm{GV}. \end{aligned} \tag{2}$$

These are pure empirical formulas although the high-energy increase of the diffusion coefficient with rigidity is natural if the efficiency of cosmic ray confinement in the Galaxy is decreasing with energy. The increase of diffusion coefficient at $R < 3$ GV has no evident physical explanation. The possible physical explanations of this effect will be considered in Section 2 in the models based on the kinetic theory of cosmic ray diffusion in the interstellar magnetic fields. The plot (a) in Fig. 2 show how the data on B/C ratio are reproduced in the plain diffusion model (2). The plots (b) and (c) refer to the two "physical" models.

The necessary degree of complexity and detalization of the galactic model employed in cosmic ray research depends on the specific problem under the investigation. A simple "leaky box" approximation may work in some cases. Under this approximation, the transport of cosmic rays in the Galaxy is described by some escape time T_{lb}, so that the terms $(-\nabla(\mathbf{D}_{xx}\nabla F) + \nabla(\mathbf{u}\,F))$ in Eq. (1) are substituted by the term F/T_{lb}. No spatial dependence of cosmic ray distribution, source density, escape time, and any other parameters are taken into account in the leaky box approximation. It can be shown that for an observer in the galactic disk and for the calculations of abundances of not very heavy stable nuclei, the leaky box model gives the same results as a flat halo diffusion model. The escape length, $X = \langle\rho\rangle\, vT_{lb}$ ($\langle\rho\rangle$ is the mean density of interstellar gas in the volume of cosmic ray propagation), the parameter which determines the nuclear spallation of cosmic rays in the leaky box model, can be expressed in the terms of the diffusion model as

$$X = \mu v H/(2D), \tag{3}$$

where $\mu \approx 2.5$ mg is the surface gas density of Galactic disk.

The escape length which corresponds to the diffusion coefficient in the plain diffusion model (2) is

$$X = 19\beta^3\ \mathrm{g/cm^2} \quad \text{at } R \leqslant 3\ \mathrm{GV}, \quad X = 19\beta^3 (R/3\ \mathrm{GV})^{-0.6}\ \mathrm{g/cm^2} \quad \text{at } R > 3\ \mathrm{GV}. \tag{4}$$