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COSMIC RAY DIFFUSION WITH AN ALLOWANCE FOR ANISOTROPY THE INTERPLANETARY MAGNETIC FIELD FLUCTUATIONS

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The small-scale collision integral in an approximation of a weak regular magnetic field is transformed using unequal parallel and perpendicular correlation lengths to the regular magnetic field. The collision frequency, the tensor spatial diffusion, and the mean free path of the cosmic rays (CR) are determined. It has been indicated that the mean free path of CR particles can increase several ten times in high-speed solar wind streams in a strongly anisotropic random interplanetary magnetic field (IMF) at small parallel correlation lengths.

1.Introduction

Experimental data indicate that the distribution of the IMF random component is aniso-tropic. This anisotropy is shown in distribution of the direction of magnetic field fluctuations and wavevectors ($\vec{k}$)of a random field, as well as in the inequality of correlation lengths entering into the correlation functions for different wavevector components. The anisotropy of wavevectors and of IMF fluctuation directions in the near-Earth space is on average insignificant: the component of wavevectors and of magnetic field fluctuations in the distinguished directions change by not more than a factor of 2-3 [Toptygin,1985; Sari and Valley, 1976]. Random structures, both extended along the mean field and flattened can predominate depending on the position relative to the Sun and on the level of solar activity, [Veselovskii and Tarsina,2001;Bavassano and Bruno, 1989; Burlaga et al., 1989; Roberts, 1990; Sari and Valley, 1976]. Using experimental data, Matthaeus et al,[1990], Völk and Alpers [1975] showed that IMF random fluctuations are mainly of two types. They are the fluctuations whose wavevectors (1) lie mostly in the $\vec{u}$ - $\vec{H}_0$ plane (slablike Alfvenic fluctuations) and (2) are perpendicular to $\vec{H}_0$ (two-dimensional fluctuations).

The anisotropy of magnetic field fluctuations is strong in the high-speed solar wind streams. Assuming that solar wind turbulence can be caused by Alfven and magnetosonic waves, Carbone et al.,[1995], showed that the maximal correlation lengths correspond to the wavevectors lying in the plane perpendicular to $\vec{H}_0$ for Alfven waves or to wavevectors perpendicular to the $\vec{u}$ - $\vec{H}_0$ plane for magnetosonic waves, where $\vec{u}$ is solar wind velocity and $\vec{H}_0$ is the strength of a regular magnetic field. In this case random magnetic structures flattened in the direction of a regular magnetic field are predominant. Maximal correlation lengths can be several ten times as large as minimal lengths. For Alfven waves in the high-speed streams, spectral index of a random field (ν) decreases and depends on a wave type and distance to the Sun. The absolute value of the magnetic field fluctuations is close to the absolute value of regular magnetic field. March and Tu [1990] have calculated several spectra of magnetic field magnitude. These authors found that in high-speed streams the spectra of of magnetic field fluctuations becomes much flatter, the spectral index being close to 0.5-0.7. Therefore, the present work has considered CR scattering in IMF in an approximation of small-scale random scattering [Dolginov, Toptygin, 1966, 1968; Toptygin, 1985]. The above researchers also indicate that, in a first approximation, the fluctuations of IMF and random field wavevectors in the solar wind can be considered axially symmetric about $\vec{H}_0$.

2. Transformation of the Collision Integral

The kinetic equation for distribution function $F(\vec{r},\vec{p},t)$, averaged over a small-scale random magnetic field has the form [Dolginov,Toptygin,1966,1968;Dorman,1975;Toptygin,1985]:

$$\left\{\frac{\partial}{\partial t}+\vec{v}\frac{\partial}{\partial \vec{r}}-\frac{p}{R_0}\vec{h}_0\vec{d}\right\}F(\vec{r},\vec{p},t)=StF \quad , \qquad (1)$$

where $\vec{r}$, $\vec{v}$, $\vec{p}$ are the coordinate, velocity, and momentum of a particle, respectively; t is time; R_0 = cp/eH_0, $\vec{H}_0 = H_0\cdot\vec{h}_0$, $\vec{d}=[(\vec{v}-\vec{u})\times\frac{\partial}{\partial\vec{p}}]$, $\vec{u}$ is magnetic field velocity,

$$StF = D_\alpha\int_0^\infty d\tau B_{\alpha\beta}(\vec{r},\Delta\vec{r}(\tau)-\vec{u}\tau)\cdot\exp\{-\Delta\vec{p}(\tau)\cdot\frac{\partial}{\partial\vec{p}}\}\cdot D_\beta F(\vec{r}-\vec{v}\tau,\vec{p},t-\tau) \quad ,$$

(2)

$\vec{D}=\frac{e}{c}\vec{d}$, $\Delta\vec{r}(\tau)$ and $\Delta\vec{p}(\tau)$ are the changes of the particle radius vector and momentum in regular magnetic field at a distance approximately equal to the maximal correlation length,

$$\Delta\vec{r}(\tau)=\vec{v}_{\parallel}\tau+\vec{v}_{\perp}\tau \ , \ \Delta\vec{p}(\tau)=0 \ .$$

It is considered that a random magnetic field contains many types of disturbances and has a fractal structure [Burlaga and Klein, 1986; Burlaga 1991(a,b); Feynman and Ruzmaikin, 1994; Zelenyi and Milovanov, 1997] ; therefore, it is rather justified to select the tensor part of the correlation tensor in an isotropic form :

$$B_{\alpha\beta}(\vec{k},\vec{r})=P(\vec{k},\vec{r})\left\{\delta_{\alpha\beta}-k_\alpha k_\beta\cdot k^{-2}\right\},\ P(\vec{k},\vec{r})=A_\nu k^2(q_\perp q_\parallel)^{-2-\frac{\nu}{2}}\left[1+\frac{k_\parallel^2}{q_\parallel^2}+\frac{k_\perp^2}{q_\perp^2}\right]^{-2-\frac{\nu}{2}} \quad ,$$

(3)

where A_ν is the normalization constant, $\vec{k}$ is the wave vector, ν is the spectral index ,

$$\vec{k}_\parallel=(\vec{k}\vec{h}_0)\vec{h}_0,\vec{k}_\perp=\vec{k}-\vec{k}_\parallel,\vec{q}_\parallel=(\vec{q}\vec{h}_0)\vec{h}_0,\vec{q}_\perp=\vec{q}-\vec{q}_\parallel,q_\perp=2\pi L_\perp,q_\parallel=2\pi L_\parallel,$$

$$B_{\alpha\beta}(\vec{x},\vec{r})=\int d\vec{k}\cdot B_{\alpha\beta}(\vec{k},\vec{r})\cdot\exp\left\{i\vec{k}\left(\vec{x}-\vec{u}\tau\right)\right\}.$$

We now represent the correlation tensor in the form:

$$B_{\alpha\beta}(\vec{x},\vec{r})=\frac{1}{3}\left\langle H_1^2(\vec{r})\right\rangle\left\{\Psi\left(x_\parallel,x_\perp\right)\delta_{\alpha\beta}-\Psi_1\left(x_\parallel,x_\perp\right)x_\alpha x_\beta\cdot x^{-2}\right\}$$

Using the transformation and the standard integrals, we obtain Ψ and Ψ_1. Substituting the correlation tensor in the collision term , we finally obtain the averaged collision integral:

$$\mathrm{StF}=\left(d_\alpha\frac{p^2}{2\Lambda_\nu\left|\vec{v}-\vec{u}\right|}d_\alpha\right)F(\vec{r},\vec{p},t)\quad, \tag{4}$$

where

(5)

$\Lambda_\nu=$

$$\frac{2\Gamma(\nu/2\text{-}1/2)}{\sqrt{\pi}\Gamma(\nu/2)}R_1^2\left[\frac{\left(\vec{v}-\vec{u}\right)_\parallel^2 q_\parallel^2}{\left(\vec{v}-\vec{u}\right)^2}+\frac{\left(\vec{v}-\vec{u}\right)_\perp^2 q_\perp^2}{\left(\vec{v}-\vec{u}\right)^2}\right]^{1/2}\left[1-\frac{\left(\vec{v}-\vec{u}\right)_\parallel^2 q_\parallel^4+\left(\vec{v}-\vec{u}\right)_\perp^2 q_\perp^4}{\left(q_\parallel^2+2q_\perp^2\right)\left[\left(\vec{v}-\vec{u}\right)_\parallel^2 q_\parallel^2+\left(\vec{v}-\vec{u}\right)_\perp^2 q_\perp^2\right]}\right]^{-1}$$

,

$R_1=cp/e\left\langle H_1^2\right\rangle^{1/2}$.

3. Diffusion Approximation

We now consider a diffusion approximation in the kinetic equation (1) with the collision term (4), (5). We will substitute the distribution function expansion

$$F(\vec{r},\vec{p},t)=\frac{1}{4\pi}N\left(\vec{r},p,t\right)+\frac{3}{4\pi v^2}\left(\vec{v}\vec{J}\left(\vec{r},p,t\right)\right)$$

in the kinetic equation (1) and will obtain the set of equations for $N\left(\vec{r},p,t\right)$ and $\vec{J}\left(\vec{r},p,t\right)$, which coincides with the set of equation for the isotropic case. The form of the spatial diffusion tensor $\kappa_{\alpha\beta}$ also remains the same as in the isotropic case [Dorman, 1975; Toptygin, 1985; Mel'nikov, 1996]:

$$\kappa_{\alpha\beta}=\frac{1}{3}\Lambda v\left(1+\Lambda^2R_0^{-2}\right)^{-1}\left\{\delta_{\alpha\beta}+\Lambda^2R_0^{-2}h_{0\alpha}h_{0\beta}+\Lambda R_0^{-1}\varepsilon_{\alpha\beta\gamma}h_{0\gamma}\right\}\quad.$$

Only the formula for the mean free path Λ changes,

$$\Lambda=8\Gamma((\nu\text{-}1)/2)\left[3\sqrt{\pi}\Gamma(\nu/2)\right]^{-1}q_\parallel R_1^2\Lambda_q\quad, \tag{6}$$

where

$$\Lambda_q=\frac{q_\parallel^2+2q_\perp^2}{q_\perp^2}\left[\frac{7}{3}+\frac{q_\perp^2}{3q_\parallel^2}-\frac{\left(2q_\parallel^2-q_\perp^2\right)q_\parallel}{q_\parallel^2-q_\perp^2}\left(\mathrm{arth}\left(\frac{\sqrt{q_\parallel^2-q_\perp^2}}{q_\parallel}\right)-\frac{\sqrt{q_\parallel^2-q_\perp^2}}{q_\parallel}-\frac{\left(q_\parallel^2-q_\perp^2\right)^{3/2}}{3q_\parallel^3}\right)\right]^{-1}$$

.

From this formula it follows that the mean free path slightly differs from its value in isotropic case at $L_\perp \ll L_\parallel$ and $L_\perp \approx L_\parallel$.But, the mean free path Λ tends to the infinity in a sharply anisotropic small-scale random magnetic field at $L_\perp >> L_\parallel$. In this case random magnetic structures are flattened in the direction of a regular field. This increased mean free path can explain experimentally obtained large paths of CRs with energies to several GeV in the solar proton events in corotating structures in the solar wind. The obtained mean free path can also explain large paths of electrons and protons with energies of tens keV to several MeV in the inner heliosphere and solar corona [Palmer,1982; Kolomeets, Sevost'yanov, 1987].

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