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Angular distribution of cosmic rays in the interplanetary magnetic field

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Abstract. Cosmic ray propagation in the interplanetary medium is considered on the basis of kinetic equation describing the scattering of charged particles by magnetic irregularities and their focusing by regular interplanetary magnetic field. The relationship between cosmic ray distribution function and parameters of particle scattering in the interplanetary medium is investigated. Obtained results are applied to the analyses of solar proton events and galactic cosmic ray anisotropy.

1 COSMIC RAY DISTRIBUTION FUNCTION

Angular distribution of energetic charged particles contains valuable information about particle scattering in the heliosphere and the geometry of interplanetary magnetic field (IMF) (Bieber and Pomerantz, 1983; Beeck and Wibberenz,1986; Wibberenz and Green, 1988; Hatzky and Wibberenz, 1997). In the present paper the relationship between the distribution function of cosmic rays (CR) and parameters of particle scattering is investigated. The kinetic equation describing CR propagation in the interplanetary medium, can be written as (Earl,1981; Toptygin,1985)

$$\frac{\partial f}{\partial t} + v\mu\frac{\partial f}{\partial z} + \frac{v}{2\zeta}(1-\mu^2)\frac{\partial f}{\partial \mu} - \frac{\partial}{\partial \mu}D_{\mu\mu}\frac{\partial f}{\partial \mu} = Q, \qquad (1)$$

where f is CR distribution function, $D_{\mu\mu}$ is the diffusion coefficient in angular space, $\mu = \cos\theta$ and θ is the pitch angle, ς is the focusing length, and z is a coordinate directed along regular magnetic field. The particle source is included in the right hand side of Eq(1).

One can present the distribution function as a superposition of isotropic f_0 and anisotropic $\delta f(\mu)$ components

$$f(z,\mu,t) = \frac{1}{2}f_0(z,t) + \delta f(z,\mu,t). \qquad (2)$$

Assuming that the particle source Q is isotropic and subtracting from Eq.(1) averaged over μ equation, we obtain

$$\frac{\partial \delta f}{\partial t} + v\left\{\frac{\partial}{\partial z} + \frac{1}{\varsigma}\right\}\left\{\mu\delta f - \frac{1}{2}\int_{-1}^{1} d\mu\mu\delta f\right\} +$$
$$+ \frac{v\mu}{2}\frac{\partial f_0}{\partial z} = \frac{\partial}{\partial \mu}\left\{D_{\mu\mu}\frac{\partial \delta f}{\partial \mu} - \frac{v}{2\varsigma}(1-\mu^2)\delta f\right\}. \qquad (3)$$

If the diffusion approximation holds one can neglect the first and the second terms in the left hand side of Eq.(3) and derive the following expression for anisotropic component of particle distribution function (Beeck and Wibberenz, 1986; Wibberenz and Green, 1988)

$$\delta f(\mu) = -\frac{\varsigma}{2}\frac{\partial f_0}{\partial z}\left\{\frac{2\exp[G(\mu)]}{\int_{-1}^{1} d\mu \exp[G(\mu)]} - 1\right\}, \qquad (4)$$

where function $G(\mu)$ is defined as

$$G(\mu) = \frac{v}{2\varsigma}\int_{0}^{\mu}\frac{1-\mu^2}{D_{\mu\mu}} \qquad (5)$$

The distribution function (2) takes the form

$$f(\mu) = \frac{f_0}{2}\left\{1 + \frac{\xi}{3}\,\frac{2\exp[G(\mu)] - \int_{-1}^{1} d\mu\exp[G(\mu)]}{\int_{-1}^{1} d\mu\mu\exp[G(\mu)]}\right\}, \qquad (6)$$

where

$$\xi = 3\frac{\int_{-1}^{1} d\mu\mu f}{\int_{-1}^{1} d\mu f} \qquad (7)$$

is the anisotropy of CR distribution.

Under isotropic scattering the pitch angle diffusion coefficient is given by

$$D_{\mu\mu} = \frac{v}{2\Lambda}(1-\mu^2), \qquad (8)$$

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where Λ is the mean free path. In the case of isotropic scattering function $G(\mu)$ (5) is proportional to μ and distribution function (6) takes the form

$$f(\mu) = \frac{1}{2} f_0 \left\{ 1 + \xi \, \frac{\lambda}{3} \, \frac{\lambda \exp[\lambda\mu) - \sinh\lambda}{\lambda \cosh\lambda - \sinh\lambda} \right\}, \qquad (9)$$

with

$$\lambda = \frac{\Lambda}{\varsigma}. \qquad (10)$$

Note that the distribution function (9) depends on μ exponentially due to magnetic focusing of particles in the IMF.

It is well known that the scattering of charged particles moving perpendicular to the mean magnetic field is significantly decayed (Beeck and Wibberenz, 1986; Wibberenz and Green, 1988; Schlickeiser, 1989). Let us introduce the coefficient of diffusion in angular space in the following form

$$D_{\mu\mu} = \frac{v}{2\Lambda} \{1 + \beta P_2(\mu)\}(1 - \mu^2), \qquad (11)$$

where $P_2(\mu)=(3\mu^2 - 1)/2$ is Legendre polynomial of the second order and parameter β describes the anisotropy of particle scattering with $\beta = 0$ for isotropic scattering. The parameter β satisfies the conditions $0 \leq \beta < 2$; the anisotropy of scattering increases and the scattering near $\mu = 0$ decreases with increasing of β. Note that phenomenological formula (11) differs from usually used expression for $D_{\mu\mu}$ (Earl, 1981; Beeck and Wibberenz, 1986; Bieber et al., 1986).

If the scattering is anisotropic, so that the diffusion coefficient $D_{\mu\mu}$ is described by Eq.(11) CR distribution function is given by expression (6) with

$$G(\mu) = \frac{2\lambda}{\sqrt{3\beta(2-\beta)}} \arctan \frac{3\beta\mu}{\sqrt{3\beta(2-\beta)}}. \qquad (12)$$

It follows from derived expressions (6),(12) that the anisotropic part of CR distribution function decrease with time proportional to particle anisotropy ξ (7).

2 DISCUSSION

The energetic particle distribution function can be written as an expansion into Legendre polynomials and these expansion coefficients can be used to study the process of particle scattering in the interplanetary medium (Beeck and Wibberenz, 1986; Bieber et al., 1986; Wibberenz and Green, 1988; Hatzky and Wibberenz, 1997; Fedorov, 1999). Starting from experimental values of expansion coefficients one can estimate parameters describing the intensity and anisotropy of scattering (Λ and β).

The angular distributions of protons in energy interval 4-13 MeV detected in the solar event on April 8, 1978 was analyzed in the paper of Beeck and Wibberenz (1986). The spacecraft Helios-1 was at heliocentric distance 0.52 AU during this event, so if we use the solar wind speed value $u = 3.9{*}10^7\ cm{*}s^{-1}$ which is inherent for this period (Beeck and Wibberenz, 1986), and Parker model of IMF, we can obtain for focusing length a value $\varsigma = 0.33$. Our calculations based on experimental data of Helios-1 (Beeck and Wibberenz, 1986) result in $\lambda = 1.8$ and $\beta = 1.6$. Therefore we obtain the value of mean free path $\Lambda = 0.6$ AU. The distribution of 0.5 MeV electrons in the same event also corresponds to prolonged anisotropy and weak scattering intensity (Beeck and Wibberenz, 1986). According to our calculations $\Lambda = 0.4$ AU; $\beta = 1.8$. Thus large value of the mean free path and significant anisotropy of scattering are characteristic for this event.

The angular distributions of protons and electrons during solar CR event April 11,1978 were near isotropic. The data registered by spacecraft Helios-2, which was at the heliocentric distance 0.49 AU, are not contrary to isotropic scattering (Beeck and Wibberenz, 1986). Under solar wind velocity $u = 4.6 * 10^7\ cm * s^{-1}$ (Beeck and Wibberenz, 1986) one can estimate the focusing length as $\varsigma = 0.29$ AU. According to our calculations for electrons with mean energy 0.5 MeV $\lambda = 0.05$, so we obtain small mean free path value $\Lambda = 0.01$ AU. Thus in this case we have significant scattering intensity. In the paper of Cramp et al. (1993) on the base of neutron monitors data the distribution function of solar CR in the event September 29, 1989 was derived. Using this function we obtain following values of parameters characterizing the intensity and anisotropy of scattering: $\lambda = 0.24$; $\beta = 0.6$. Under solar wind velocity $u = 4 * 10^7\ cm * s^{-1}$ this value of λ corresponds to the mean free path $\Lambda = 0.2$ AU. The presented estimates show that both scattering intensity and anisotropy vary significantly from event to event. So for quoted solar flares the mean free path ranges from 0.01 to 0.6 astronomical unit, and parameter β varies from 0 to 1.8.

The anisotropy of galactic CR distribution is responsible for daily variations of CR intensity observed on worldwide network of neutron monitors. The first 3 harmonics of CR diurnal variation registered by Swathmore neutron monitor were investigated by Bieber and Pomerantz (1983). Using these data the scattering intensity and anisotropy were estimated and the value $\Lambda = 0.5$ AU for protons with 10 GV rigidity was obtained (Bieber and Pomerantz,1983). According to our calculations the anisotropy of scattering is relatively small ($\beta = 0.24$) in agreement with Bieber and Pomerantz (1983). For the particle mean free path we obtain $\Lambda = 0.3$ AU which is somewhat below the value derived by Bieber and Pomerantz (1983).

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