THE FIRST THREE HARMONICS OF SOLAR DAILY VARIATION CAUSED BY THE DIFFUSIVE PROPAGATION OF GALACTIC COSMIC RAYS THROUGH THE HELIOSPHERE

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Introduction

Forming a complement to our preceeding paper(1), we present some results for the first three harmonics derived from the simulation of diffusion-convection of galactic cosmic rays. We present also some dependences of the results to the modulation parameters. The results are discussed in comparison with observations and with the former studies of higher order anisotropy.

In addition to this, we suggest the existence of the IMF-sense-dependent anisotropy of higher order which is discussed in detail in a separate paper(2).

Theory and Model

The cosmic ray anisotropy $\eta(r, p)$ can be expressed as

$$\eta(r,p) \sim 1+\sum_{n=1}^{3}\sum_{m=0}^{n}\{\eta_n^{mc}(r,p)\cos(m\Phi')+\eta_n^{ms}(r,p)\sin(m\Phi')\}P_n^m(\cos\Theta'), \qquad (1)$$

where Θ' and Φ' express the incident direction of cosmic rays, defined as(cf. Fig.1)

$$\Theta'=\pi-\Theta, \qquad \Phi'=\pi+\Phi,$$

and

$$\eta_n^{mc}(r,p)=(-1)^n F_n^{mc}(r,p)/F_0^{0c}(r,p),$$

$$\eta_n^{ms}(r,p)=(-1)^n F_n^{ms}(r,p)/F_0^{0c}(r,p).$$

As shown in our preceeding paper(1), F_n^{mc} and F_n^{ms} in Eq.(1) are given by the cosmic ray density U, stream S_i, stress tensor T_{ij} and heat flow tensor H_{ijk} which are governed by the following equations.

$$\nabla\cdot(CUV-\underline{\underline{\kappa}}^{(1)}\cdot\nabla U)=-\frac{\partial}{\partial p}(\frac{1}{3}pV\cdot\nabla U), \qquad (2)$$

$$S=CUV-\underline{\underline{\kappa}}^{(1)}\cdot\nabla U, \qquad (3)$$

$$T_{ij}=-\kappa^{(2)}{}_{ijfg}(\overset{\circ}{\overline{\nabla S}})_{fg}, \qquad (4)$$

$$H_{ijk}=-\kappa^{(3)}{}_{ijkfgh}(\overset{\circ}{\overline{\overline{\nabla \underline{\underline{T}}}}})_{fgh}. \qquad (5)$$

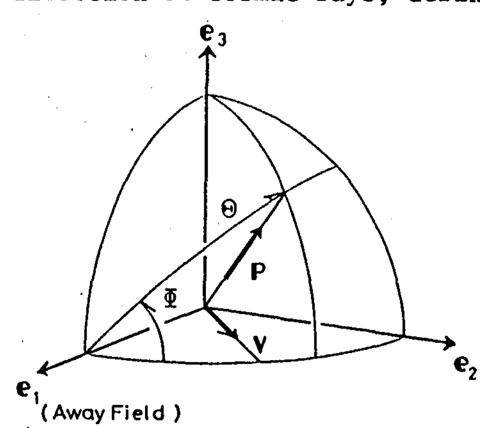

Fig.1 IMF-COORDINATE SYSTEM

p ; Particle's momentum.
V ; Solar wind velocity.
$\mathbf{e}_1$; Unit vector in the direction of **B** in the 'away' sector.
$\mathbf{e}_3=\mathbf{e}_1\times\mathbf{V}/|\mathbf{e}_1\times\mathbf{V}|$.
$\mathbf{e}_2=\mathbf{e}_3\times\mathbf{e}_1$.

where

$$(\overset{\circ}{\overline{\nabla S}})_{fg}=\frac{1}{2}\left[\frac{\partial S_f}{\partial x_g}+\frac{\partial S_g}{\partial x_f}+S_q(Z_{qfg}+Z_{qgf})\right]-\frac{1}{3}(\nabla\cdot S)\delta_{fg}, \qquad (\nabla\cdot S)=\frac{\partial S_q}{\partial x_q}+S_qZ_{qrr},$$

and

$$Z_{ijk}=\frac{\partial \boldsymbol{e}_i}{\partial x_j}\cdot\boldsymbol{e}_k=-Z_{kji}. \qquad (6)$$

Note that, in the IMF-coordinate system, Z_{ijk}'s in Eq.(6) represent the IMF-curvature and focusing. We first solve Eq.(2) in the model heliosphere and, starting from the solution for U, we can calculate successively S_i, T_{ij} and H_{ijk} by Eqs.(3)-(5). In these calculations, the following scattering m.f.p. is assumed.

$$\lambda=\lambda_0(R/\mathrm{GV})\exp\left(\frac{r-r_e}{33\mathrm{a.u.}}\right)(1+a_\lambda\cos\theta_H), \qquad (7)$$

where λ_0 and a_λ are the parameters, R is the rigidity and θ_H is the polar angle in the heliocentric polar coordinate system. The calculations were carried out for various values of λ_0 and a_λ and, in this paper, the results in the following two cases will be presented.

case I .... λ_0 = 0.016 a.u. and $0\leq a_\lambda\leq 3$,

case II .... λ_0 = 0.032 a.u. and $0\leq a_\lambda\leq 3$.

It is noteworthy that, in Eqs.(3)-(5), S_i, T_{ij}, H_{ijk} having subscript '3' odd times are IMF-sense-dependent and their associated anisotropies symbolized by η_n^{ms} with mark '*s*' change their signs according to the alteration of the 'away' and 'toward' sectors whereas η_n^{mc} with mark '*c*' do not. In this paper, we restrict ourselves only to η_n^{mc}, and the natures of η_n^{ms} mentioned above will be discussed in a separate paper(2).

Results and Discussions

The anisotropies η_n^{mc}'s in space can be expressed by the surface harmonics in the equatorial coordinate system and can be observed as solar daily variations at the Earth(3).

The resultant first space harmonic vectors for cases I and II are shown in Fig.2, with black characters in the positive state and white characters in the negative state. It can be clearly seen that the harmonic vector in the positive state changes its phase toward earlier hours from that of 18h in the negative state, in accordance with the observed 22-year variation of the diurnal variation(4,5,6).

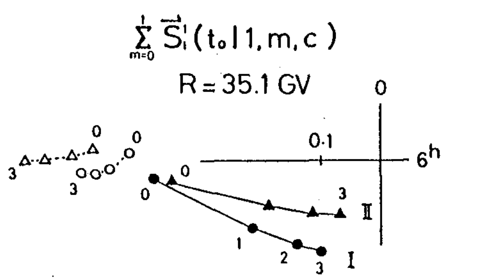

Fig.2 FIRST SPACE HARMONIC VECTORS

Arabic numerals represent the value of a_λ in Eq.(7). The black and white characters represent the positive and negative polarity states, respectively.

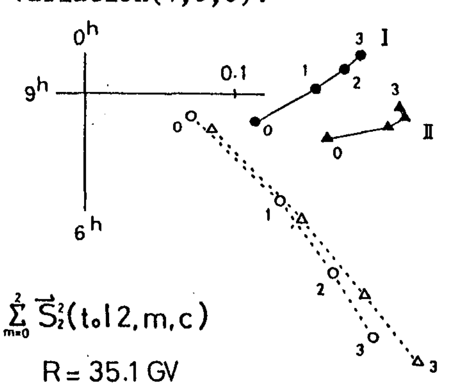

Fig.3 SECOND SPACE HARMONIC VECTORS

The resultant second space harmonic vectors are shown in Fig.3. These vectors in both polarity states are mainly due to the η_2^{0c}-type anisotropy which is independent of Φ (cf. Eq.(1)). The magnitude η_2^{0c} of the anisotropy includes three terms expressing, respectively, the spatial derivatives of S_i, the IMF-curvature effect and the IMF-focusing effect. On the basis of simulations, it is found that all these terms have significant contribution to the anisotropy and the IMF-focusing effect is not always most predominant. A similar Φ- independent anisotropy was obtained also by Bieber and Pomerantz(7), on the basis of the following diffusion equation with respect to the pitch angle cosine ($\mu=\cos\Theta$).

$$\frac{\partial f(\mu,x_1,t)}{\partial t}+\mu v\frac{\partial f(\mu,x_1,t)}{\partial x_1}-\frac{\partial}{\partial\mu}D_{\mu\mu}\frac{\partial f(\mu,x_1,t)}{\partial\mu}+\frac{v}{2L}(1-\mu^2)\frac{\partial f(\mu,x_1,t)}{\partial\mu}=0, \qquad (8)$$

where $D_{\mu\mu}$ is the Fokker-Planck coefficient for pitch angle scattering and L is the focusing length of IMF(8). They concluded that the anisotropy is principally a result of the focusing effect of IMF represented by the last term in Eq.(8). This anisotropy can be regarded as a special case which is applicable only for one dimensional diffusion along the IMF with infinite radius of curvature in the equatorial plane. In other words, this special anisotropy lacks the term expressing the IMF-curvature effect which has a dominant influence on the anisotropy as pointed out previously.

Turning to the third order anisotropy, we obtained two dominant terms η_3^{0c} and η_3^{1c}. The eigen phases of the tri-diurnal variation arising from these two terms are almost orthogonal to each other, that is, (1h,5h) from η_3^{0c} and (3h,7h) from η_3^{1c}. It is noteworthy that one of the eigen phases(3h,7h) arising from η_3^{1c} coincides with the observed phase around 7h in local time(9,10). Since the η_3^{1c}-type distribution is not symmetrical with respect to the field, this implies that the angular

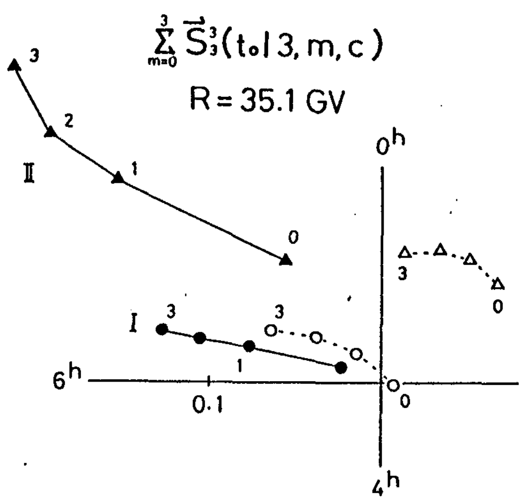

Fig.4 THIRD SPACE HARMONIC VECTORS

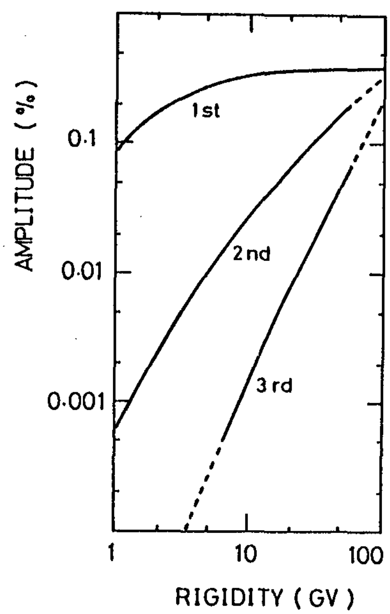

Fig.5 RIGIDITY SPECTRA OF THE FIRST THREE HARMONICS

distribution of the third order anisotropy can not expressed generally in terms of only the pitch angle cosine μ. In this respect, it is not suitable to discuss the third order anisotropy on the basis of the diffusion equation of Eq.(8). Fig.4 shows the resultant tri-diurnal variations which are mainly composed of the above mentioned two types of distribution, i.e., η_3^{0c} and η_3^{1c}. It is noted that the tri-diurnal variations obtained show polarity dependence. This dependence, however, is sensitive to the modulation parameters and, for instance, in case I we can get almost a polarity independent variation with increasing a_λ.

Lastly, Fig.5 shows the rigidity spectra of the first three harmonics obtained in case I for $a_\lambda=0$. The spectrum of the higher harmonic rises more steeply than that of the lower harmonic, and in the high rigidity region, the spectra of the second and third harmonic are almost proportional, respectively, to R and R^2. This is due to λ linearly increasing with rigidity R(cf. Eq.(7)). Such a rigidity dependence is consistent with the observations(*10*,*11*).

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