# INTERPRETATION OF COSMIC-RAY ANISOTROPY BELOW $10^{14}$ eV

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We have found that the measured data on the degree of anisotropy of cosmic rays are consistent with our proposed nonuniform galactic disk model. Moreover, we point out that the abrupt increase of the anisotropy of cosmic rays beyond $10^{14}$ eV should imply a change of their mass composition.

It appears that a nearly constant degree of anisotropy of cosmic rays ($\delta$) below $10^{14}$ eV is in conflict with the usual leaky box model(1). Thus it is interesting to examine the cosmic-ray anisotropy calculation in our proposed nonuniform galactic disk (NUGD) model(2).

In the NUGD model the observed $\delta$ value should be characteristic of the magnetic tube (Box 1 in Fig. 1 of OG 7.2-10), because the solar system is assumed to be located inside it. Along the magnetic tube cosmic-ray protons should present a streaming motion. It is adequate to describe this motion by using a one-dimensional slab model

$$\frac{dN_{pI}}{dx_I} = - \frac{N_{pI}}{\lambda_p^i} + \int_{E_p}^{\infty} \frac{1}{\lambda_p^i} \frac{dN_p(E_p,E'_p)}{dE_p} N_{pI}(E'_p)dE'_p \quad , \tag{1}$$

where $N_{pI}$ is the proton intensity in Box 1, $x_I$ is the pathlength travelled by cosmic rays along the magnetic tube, $E_p$ is the total energy of a proton, $\lambda_p^i$ is the mean inelastic interaction length of interstellar protons and $dN_p/dE_p = 1/E'_p$ is the energy distribution of protons after their inelastic interactions with the interstellar medium(ISM). At high energies the diffusive motion approximation of cosmic rays means

$$x_I = x_{0I} E_p^{-\delta_e} , \tag{2}$$

where $x_{0I}$ is a constant and $\delta_e = 0.7(3)$. Eq. (1) then can be reduced to

$$\frac{dN_{pI}}{dx_I} = - \frac{N_{pI}}{\lambda_p^{att}} \quad , \tag{3}$$

where $\lambda_p^{att} = \lambda_p^i/(1-1/\gamma_p)$ and $\gamma_p$ is the differential spectral exponent of the high-energy proton spectrum. Hence in the solar neighbourhood the proton intensity $N_{pIs}$ should be

$$N_{pIs} = N_{p0I} \exp( - x_{0Is} E_p^{-\delta_e} /\lambda_p^{att} ), \tag{4}$$

where $N_{p0I}$ is the initial value of $N_{pI}$ and $x_{0Is} = 0.4 \lambda_p^i$ (4). For $E_p \geqslant 10^{11}$ eV the mean gradient of cosmic rays along the magnetic tube is

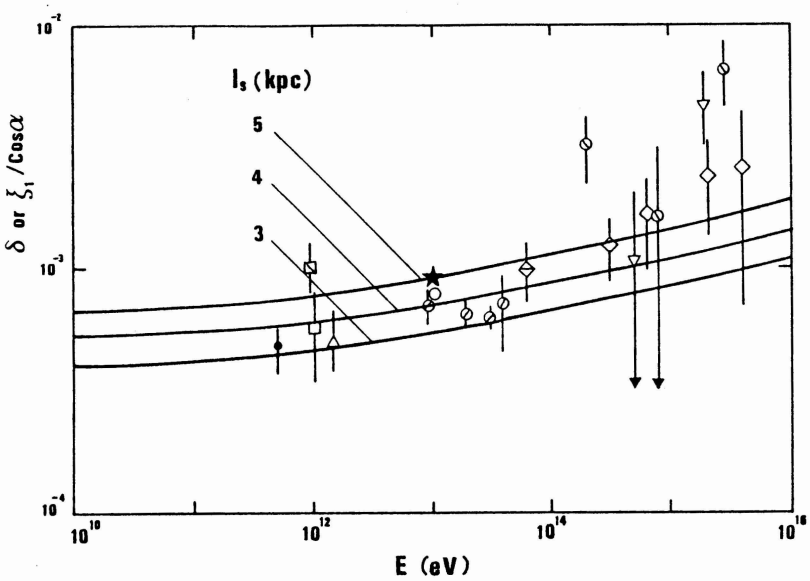


Fig. 1

$$\frac{1}{N_{pI}} \frac{dN_{pI}}{dl_I} = \frac{x_{Is}}{l_s \lambda_p^{att}} , \qquad (5)$$

where $l_s$ is the distance along the magnetic tube between the $H_2$ cloud region and the solar system. Under the diffusive motion approximation of cosmic rays we also have

$$\tau_{Is} = l_s^2 / 2\kappa_I , \qquad (6)$$

where $\kappa_I$ is the diffusion coefficient of cosmic rays in Box I and $\tau_{Is}$ is the transit time to reach the solar neighbourhood. Since

$$\tau_{Is} = x_{IS} / (m_p \bar{n}_I c), \qquad (6)$$

where $m_p$ is the proton mass, $\bar{n}_I$ is the mean hydrogen atom density of the ISM in Box I and c is the velocity of light, we can get

$$\kappa_I = m_p \bar{n}_I c l_s^2 /(2x_{Is}) , \qquad (8)$$

and the degree of anisotropy of cosmic rays(5)

$$\delta = \frac{3\kappa_I}{c} \frac{1}{N_{pI}} \frac{dN_{pI}}{dl_I} = \frac{3m_p \bar{n}_I l_s}{2 \lambda_p^{att}} . \qquad (9)$$

It is interesting to note that in Eq. (9) the increase of the cosmic-ray diffusion coefficient with energy is just compensated for by the opposite variation of the cosmic-ray intensity gradient, so that a nearly constant $\delta$ value should be obtained. In Fig. 1 the predicted $\delta$ curves are based on $\bar{n}_I$ =1.2 H atomscm$^{-3}$(6) and the value of $\lambda_p^1$ suggested in Ref. (7). An additonal increase of $\lambda_p^{att}$ is included to take the contribution of heavy nuclei in the ISM into account. From Fig. 1 the scattering of $l_s$ values estimated from various data is found to be within =± 1 kpc.

However, it should be emphasized that except the datum denoted by a star(8) the measured data collected in Ref. (9) and shown in Fig. 1 do not refer to $\delta$ itself. Thus by normalizing our predicted curve to the star we finally obtain $l_s$ = 5±1 kpc. Further, the measured data shown in Fig.1 indeed show a slightly increasing trend, which should be the first astronomical evidence of the rising of the p-p inelastic interaction cross section with increasing energy in the context of the NUGD model.

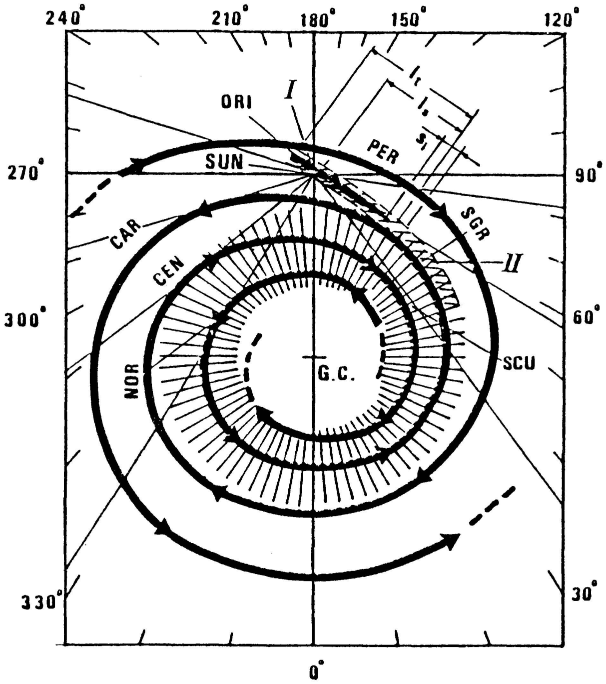


Fig. 2

From our deduced $l_s$ value we can estimate the astronomical counterpart of our model elements. In Fig. 2 the geometrical relationship between the $H_2$ cloud ring (the radially hatched region) and the large-scale interstellar magnetic field (the spirally solid lines) is shown. As the reversal of field direction occurs between the Orion arm and the Sagittarius arm, a neutral line should exist between both arms. The existence of a neutral line should obstruct the exchange of cosmic-ray particles between two adjacent arms. As a result, in the $H_2$ cloud ring only from a narrow region exterior to the Sagittarius arm (the region II in Fig.2) cosmic-ray particles can stream along the Orion arm to reach the solar neighbourhood.

Actually, in our model picture each small region including a dense $H_2$ cloud and its magnetically connected surrounding gas may be viewed as a coherent entity which is called as a cell(10). All the magnetically connected cells form a subtube and all subtubes form the magnetic tube. In view of the fluctuation of interstellar magnetic field the direction of the subtube, in which the solar system is located, may be different from the general direction of the Orion arm. Thus the measured value of the maximum phase for the 1st harmonics of cosmic-ray intensity variation may be understood.

It is noticeable that in order to avoid affecting the spectral shape of heavy nuclei, the NUGD model requires an assumption that in the distant component of cosmic rays there should exist a serious deficit of heavy nuclei. Actually, similar assumptions also appear in many other double-component models of cosmic-ray propagation. However, in our model the deficit should occur in the preacceleration stage of cosmic rays ( e.g., by an unfavourable preacceleration condition for heavy nuclei in their acceleration sites above the $H_2$ cloud region). Thus the observed heavy nuclei of cosmic rays should be of local origin. Moreover, from an analysis of the high-energy electron spectrum(4) it is found that only about 5 % of observed protons come from the local region.

Consequently, in the sample of locally produced cosmic rays the abudances of heavy nuclei relative to protons must be higher the directly observed values by a factor of 20. The assumed relative abudances of cosmic-ray nuclei in the sample of locally produced cosmic rays are shown in Fig. 3 as the horizontal lines. In Fig. 1 we have noted that an abrupt increase of the degree of anisotropy of cosmic rays occurs beyond $10^{14}$ eV. Here we try to attribute this increase to the failure of our NUGD model due to the insufficient confinement of cosmic rays at very high-energies. Therefore, at very high energies the locally produced cosmic rays would fill the intensity vacancy left by the distant component of cosmic rays. As a result, the observed abudances of cosmic-ray nuclei should approach to the local abudances shown in Fig. 3. In view of the situation that above $2\times10^{15}$ eV the dominant contribution to the observed cosmic rays may come from one single source, these abudaces may never be reached. Nevertheless, a variation of cosmic-ray mass composition with increased contribution of heavy nuclei should be expected to happen around $10^{15}$ eV.

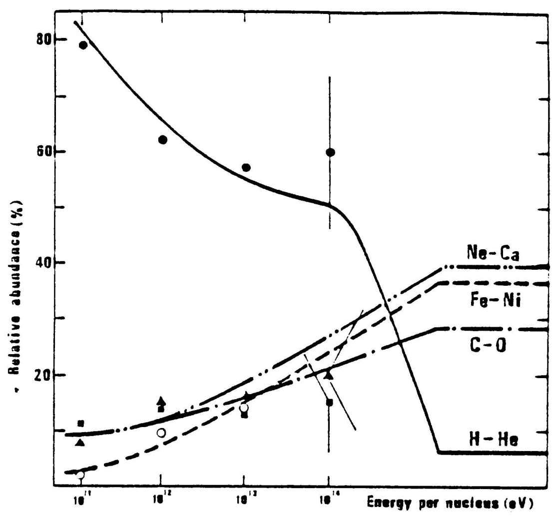


Fig. 3

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