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A MODEL FOR THE PROTON SPECTRUM AND COSMIC RAY ANISOTROPY

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1. Introduction.

The problem of the origin of the cosmic rays is still uncertain. Since the observed cosmic ray composition, spectrum and anisotropy involve a lot of factor, for example, the spectrum of the primordial cosmic rays, the mechanism of acceleration and propagation as well as the distribution of the interstellar medium and magnetic field. Unfortunately, all of these are remained open, though people gets more and more information and ideas. As a theory, it should explain the support of particles and energy, the mechanism of acceleration and propagation as well as some important features obtained directly from cosmic ray experiments, such as the power spectrum and the knee at about 10^{15}eV[1], the near constant amplitude of the first harmonic of anisotropy among 10^{11}-10^{14}eV and the amplitude varying as $E^{0.5}$ above 5×10^{15}eV[2,3]. And it should also account for the relative abundance and the flux of cosmic rays. But so far there is no model which can interpret all of these phenomena.

In a general opinion the cosmic rays of 10^{10}-10^{18}eV are the galactic origin, but above they are the extragalactic origin. People also acceptes that the cosmic rays propagate in a diffusion way, variaty of diffusion mechanism derive different diffusion coefficient as a function of energy. But anyhow diffusion always makes the energy spectrum steeper.

There are two kinds of models for interpreting the knee of the cosmic ray spectrum. One is the leaky box model[1] in which every nuclei has different escape starting rigidity, the heavier the higher, but the flux of heavy nuclei is much less. Another model[4] suggests that the cut-off rigidity of the main sources causes the knee. The present paper studies the spectrum and the anisotropy of cosmic rays in an isotropic diffuse model with explosive discrete sources in an infinite galaxy.

2. The transport equation and its solution.

In an isotropic diffusion model cosmic ray density, N(r,t,E), obeys the following equation[5]

$$\frac{\partial N}{\partial t} - D\nabla^2 N + \frac{\partial}{\partial E}(NW) + BN = Q. \qquad (1)$$

where D is the diffusion coefficient, the third term is due to energy loss, W=dE/dt, the fourth term is negitive source and Q is the source. Firstly, starte our argument from one discrete source and assume as follows:

(1) Because the ages of the main point sources within 1kpc (table.1) are about 10^4y[6], even for the highest energy proton its half lifetime(caused by Compton scattering, synchrotron radiation and bremstruhlung altogether) is several

decades to few hundred times long as its age. So we neglect the energy loss.

(2) Assume the P-P interaction contributs to the negtive source term only, $B=cn\sigma_{ine}$, where c is the speed of light, n the density of hydrogen, σ_{ine} the inelastic cross-section of P-P interaction. From accelerator experiments[7] the total cross -section of P-P is obtained among energy range $10-1.5\times10^{6}$ GeV, and $\sigma_{ine}=0.8\,\sigma_{Tot}$. Fitting these data, get the formula

$$B(E)=3\times10^{-17}[35.3-2.2(\ln E)+0.3(\ln E)^2]\ (1/s). \quad (2)$$

here n =1 has been taken.

(3) The charged cosmic rays propagate through resonant scattering with the turbulent hydromagnetic wave. Zhang et al[8] derived

$$D=\frac{1}{12\pi}\frac{\beta}{\sqrt{1-\beta^2}}\frac{\bar{B}}{e}\frac{mc^2}{\Lambda\varepsilon_B}.$$

rewrite it as

$$D=\frac{Pc}{12\pi}\frac{\bar{B}c}{e\Lambda\varepsilon_B}. \quad (3)$$

where $\bar{B}$ and ε_B is the mean intensity and energy density of the fundamental magnetic field, respectively. Λ is the fraction of turbulent in the mean field. Take $B=3\mu G$, $\Lambda=0.01$, $\varepsilon_B=0.3\,eV/cm^3$, then for the proton of greater than 10GeV,

$$D=1.67\times10^{15}E(\mathrm{cm^2/s}).$$

Table 1. List of SNR near the solar system

NAME	t(10 y)	r(kpc)	E (eV)
CTB 72	3.2	0.7	2x10
Cyg. Loop	3.5	0.6	10
HB 21	2.3	0.8	3x10
CTB 1CT	4.7	0.9	2x10
CTB 13	3.2	0.6	10
HB 9	2.7	0.8	2x10
S 149	4.3	0.7	10
Monoceros	4.6	0.6	7x10
Vela	1.1	0.4	10
Lupus	3.8	0.4	4x10
Loop	3.0	0.05	10

In general the coefficient has a form $D\propto E^{\frac{1+\nu}{2}}$, say $E^{0.5}$, but the recent data from HEAO-3 show that the index trends to rising and $D\propto E^{0.7}$ can account for the experimental data quite well. A compare shows that the diffusion coefficient adopted by our paper is close to that with the index 0.7 at high energies.

(4) The i-th point source ejects particles transiently with a spectrum $N_0E^{-\Gamma}$ at t=0. So that $Q=N_0E^{-\Gamma}\delta(r-r_i)\delta(t_i)$

Combining of all these and transforming $N=\mathcal{N}e^{-Bt}$, we get solution of Eq.(1)

$$N_i=\frac{N_0E^{-\Gamma}}{(4\pi Dt_i)^{1.5}}\exp\left[-\frac{r_i^2}{4Dt_i}-B(E)t_i\right] \quad (4)$$

where t_i is the age of the point source, r_i the radial distance with its origin at the source position. Mathematically, the formula(4) makes sense for any value of r_i and t_i, but considering the causality only such sources with $(r_i/t_i)<c$ contribute to the observed flux. So we take account such sources only.

3. The predict spectrum of proton.

From Eq.(4) see that for very old/and distant pointsource its density N_i has a very large Gaussian width, i.e.$\nabla N_i=0$, so we can treat them altogether as a background N_B. Therefor we have

$$N=N_B+\sum_i N_i \qquad (5)$$

supposing v is isotropy and neglecting higher than second harmonic anisotropy of I, then $N=4\pi I/v$, we have

$$I=I_B+\sum_i I_i \qquad (6)$$

Taking the parameters =1.5, $N=4\times10^{47}$, $I_B=2.5\times10^{4}E_{GeV}^{-2.8}(\mathrm{m.s.sr.GeV})^{-1}$ and inserting these values of r_i, t_i, of the eleven supernovea in Eq.(6), we have the result(Fig.1). You can see that the predict results fits the data of the proton quite well. In fact, because of the cut-off energy of the eleven supernovea, the value of I_B is almost uniquely determed by the data of the proton of $10^{11}-10^{12}$eV. It is clear that the time scale of change of the proton intensity $\tau>1/cn\sigma_{ine}=10^{7}$ y, it agrees with long time data of cosmic rays.

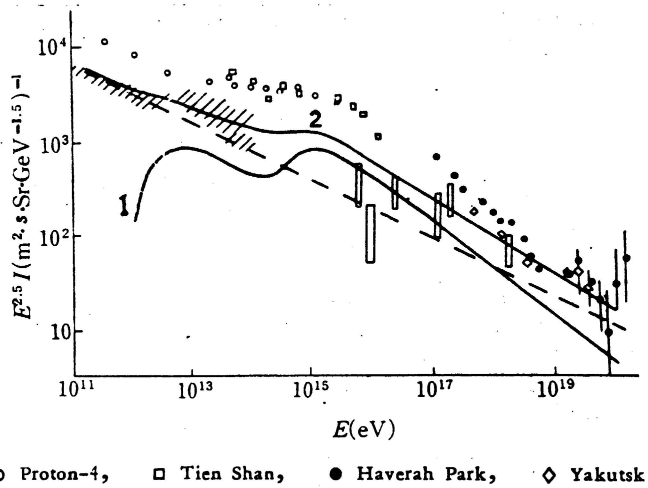

Fig. 1 The differential spectrum of primary cosmic rays Curve 1 is the sum of intensities contributed by eleven supernovae. The dashed line represents the background I_B. Curve 2 is the predicted differential spectrum of primary protons. Shaded area and sign ▯ are the data of protons, the rest are somewate contaminated by other nuclei.

4. The anisotropy of cosmic ray.

Under above mentioned case, the amplitude of first harmonic anisotropy has been obtained

$$\vec{\delta}_i=\left(\frac{3\dot{r}_i N_i}{2Ct_i N}\right)\vec{r}_{oi} \qquad (7)$$

where r_i is the unit vector from the Earth to the i-th point source. Considering the motion of the Earth with respect to the cosmic ray background there will be Compton-Getting anisotropy, independent of energy but relevant to the spectrum index

$$\delta_c=(\gamma+2)v/c \qquad (8)$$

so the final resultant anisotropy, can be expressed as

$$\vec{\delta}_F=\vec{\delta}_c+\sum_i\left(\frac{3r_i}{2Ct_i}\right)\left(\frac{N_i}{N}\right)\vec{r}_{oi} \qquad (9)$$

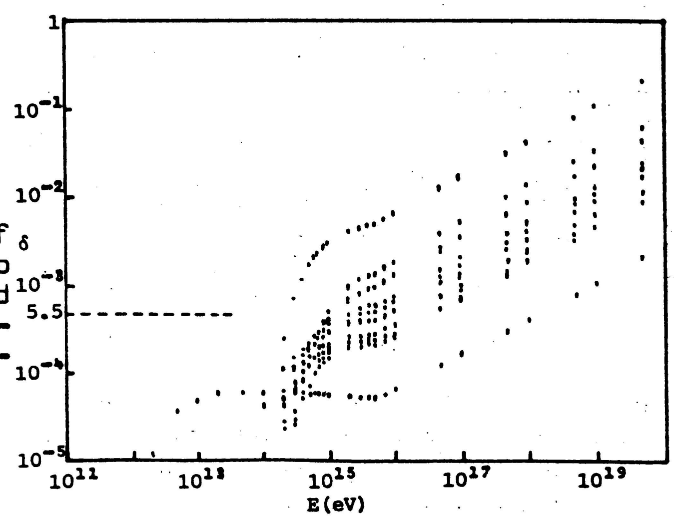

Fig.2. The expected amplitudes of the anisotropy caused by eleven SNR individually.

The experimental data show that

$$N=4\pi I/c=1.2\times10^{-3}E^{-2.66}(1/m^3) \quad \text{for } E\leq5\times10^6\,\text{GeV}$$
$$N=1.1\,E^{-3.1}(1/m^3) \quad \text{for } E>5\times10^6\,\text{GeV}$$

Inserting these values of r_i, t_i, N_i of the eleven supernovea individually and the value of N into Eq.(7), using the trial values $N_0=1.32\times10^{45}$, $\Gamma=1.2$(corresponding to the source emi-ssion 10^{50} ergs in the particle form),the anisotropies as a function of energy were calculated.The results are given in Fig.2.

We find that each of these anisotropies is smaller than 6×10^{-5} below 10^{14}eV, but varies as $E^{0.4}$ above 5×10^{15} eV.So whatever the direction of each anisotropy is, the resultant anisotropy always has a $E^{0.4}$ variation. On hte other hand, the measured anisotropies are about 5.5×10^{-4} in the energy range $10^{11}-10^{14}$eV. Combination of these information together leads us to draw the conclusion that the Compton-Getting anisotropy is dominant, $\delta=\delta_c=5.5\times10^{-4}$ below 10^{14}eV.By substituting $\gamma=2.66$ in Eq.(8), we get the velocity of 35km/s with respect to the cosmic ray background.

5. Discussion and conclusion.

The anisotropy mentioned above is in principle for proton. However, the anisotropy is dependent on the species of cosmic rays.Unfortunately,so far the identification of the species of cosmic ray in EAS is uncertain yet.Recently,a few of discrete γ-ray sources in the energy range $10^{15}-10^{16}$eV has been detected.People have noted the possible effect of γ-rays on the anisotropy and the intensity of cosmic rays[9].

The conclusion to be drawn from this study may be summarized as follows: Taking some reasonable parameters,the model can account for the features of the proton spectrum and the approximate constancy of the cosmic ray intensity in a long period.It also can interprete the power law of the anisotropy above energy 5×10^{15}eV,and the Compton-Getting effect is responsible for the anisotropies in the energy range $10^{11}-10^{14}$ eV. Furthermore, we got the streaming velocity of 35km/s with respect to the cosmic ray background.

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