On Fluctuations of Cosmic Rays in the Galaxy with Random Supernova Outbursts

V.S. Ptuskin,[1,2] F.C. Jones,[3] E.S. Seo,[2] and R. Sina[2]
(1) IZMIRAN, Troitsk, Moscow region 142190, Russia
(2) IPST, University of Maryland, College Park, MD 20742, USA
(3) NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

Abstract

The random nature of cosmic ray (CR) sources leads to the fluctuations of CR intensity in space and time. We calculate the expected fluctuations in a flat-halo diffusion model for particles with energies from 1 to 10^3 TeV. The data on CR spectrum and anisotropy, and the astronomical data on supernova remnants, the potential sources of CRs, can be used to constrain the value of CR diffusion coefficient and its dependence on energy.

1. Introduction

The SN explosions that give rise to the galactic CRs are essentially statistical events, discrete in space and time. This poses the question as to whether the fluctuations of CR density and anisotropy are significant [5]. The problem can be approached by a theoretical calculation of the average values and their fluctuations in the frameworks of "statistical mechanics of supernovae" [5,8,3], and by a calculation of the CR distribution based on the astronomical information about the actual characteristics of local SNRs [4,9]. Below we use both of these approaches and study CRs in the diffusion model with a flat halo.

2. Statistical Fluctuations of Galactic Cosmic Rays

We consider a simple flat-halo galaxy model with an infinite galactic disk radius where the coordinate z is perpendicular to the galactic plane. The CR density $N(t, \mathbf{r}, E)$ obeys the diffusion equation:

$$\frac{\partial N}{\partial t} - \nabla D \nabla N = q_0 \delta(z). \tag{1}$$

Here $D(E)$ is the scalar diffusion coefficient that does not depend on position; $q_0(t, z, E)\delta(z)$ is the source term that represents the CR production by SN bursts in a thin disk at $z = 0$. There is a CR halo boundary at $z = -H$ and $z = H$ where CRs freely exit from the Galaxy. We consider here protons with very high

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energies, $E > 1$ TeV (where the data on CR anisotropy are probably not affected by the modulation in the heliosphere), and thus ignore the ionization energy losses, the nuclear interactions with interstellar gas, and the possible reacceleration on interstellar turbulence. The CR anisotropy in the diffusion approximation is $\mathbf{A} = -3D\nabla N/cN$ (in our calculations, the appropriate correction in this equation is introduced for the sources at distances less than the diffusion mean free path). The diffusion coefficient in this model was found at energies $10^{-4} - 10^{-1}$ Tev/n [5], where the data on secondary nuclei are available. The diffusion evidently does not change its character up to the knee at 3×10^3 TeV. Thus based on [5], we accept for very high energy protons the values $D_a = 1.55E^{0.3}H_5$ kpc^2/Myr in the model with distributed reacceleration, and $D_d = 2.76E^{0.54}H_5$ kpc^2/Myr in the plain diffusion model, where E is in TeV and $H = 5H_5$ kpc.

Studying the effect of discreteness of CR sources, we assume their statistical homogeneity in the galactic disk and do not take into account a large scale gradient of galactic SNR distribution. It is assumed also that the SN rate in the galactic disk is $\sigma_{SN} = 50$ kpc^{-2}Myr^{-1}, and each SNR instantly inject $n(E)$ energetic particles in the interstellar space. The method of calculations of the average values and dispersions of cosmic ray density and anisotropy was presented in [8,3] (where it was applied to the not realistic case of an infinite 3-dimensional distribution of sources). It gives the following average values in the disk $\langle N\rangle = n\sigma_{SN}H(2D)^{-1}$, $\langle \mathbf{A}\rangle = 0$, and the dispersions:

$$\frac{\langle(\delta N)^2\rangle^{1/2}}{\langle N\rangle} = \frac{D^{1/2}}{(2\pi\sigma_{SN})^{1/2}H^2}\left(\sum_{n,m} -\mathrm{Ei}\left(-\left((n-\frac{1}{2})^2+(m-\frac{1}{2})^2\right)\frac{\pi^2 D\tau_0}{H^2}\right)\right)^{1/2} \tag{2}$$

$$\approx \frac{D^{1/2}\ln^{1/2}\left(\frac{2H^2}{\pi^2 D\tau_0}\right)}{(2\pi\sigma_{SN})^{1/2}H^2}, \quad \left\langle \mathbf{A}^2\right\rangle^{1/2} \approx \frac{3D}{2(\pi\sigma_{SN}\tau_0)^{1/2}cH^2}.$$

Here $m, n = 1, 2...\infty$; $\mathrm{Ei}(x) = \int_{-\infty}^{x} dt t^{-1}\exp(t)$ is the exponential integral; the cutoff parameter τ_0 takes into account the absence of very young and nearby sources, its typical value can be estimated as $\tau_0 = (4\pi\sigma_{SN}D)^{-1/2}$, see also [7].

Eqs. (2) allow one to estimate $\delta N/N{=}0.003H_5^{-3/2}E^{0.15}\ln^{1/2}(10^2H_5^{3/2}E^{-0.15})$, $A = 1.4 \times 10^{-4}H_5^{-3/4}E^{0.38}$ for the model with reacceleration, and $\delta N/N = 0.004H_5^{-3/2}E^{0.27}\ln^{1/2}(78H^{3/2}E^{-0.27})$, $A = 2.8 \times 10^{-4}H_5^{-3/4}E^{0.65}$ for the plain diffusion model. The amplitudes of fluctuation anisotropy expected in these two models at $H = 5$ kpc are shown in Fig. 1 by thin lines together with the observed CR anisotropy at the Earth.

3. Effect of Individual Supernova Remnants

Let us calculate the CR anisotropy, which results from the production of CRs in known local galactic SNRs. It is assumed that the background CR

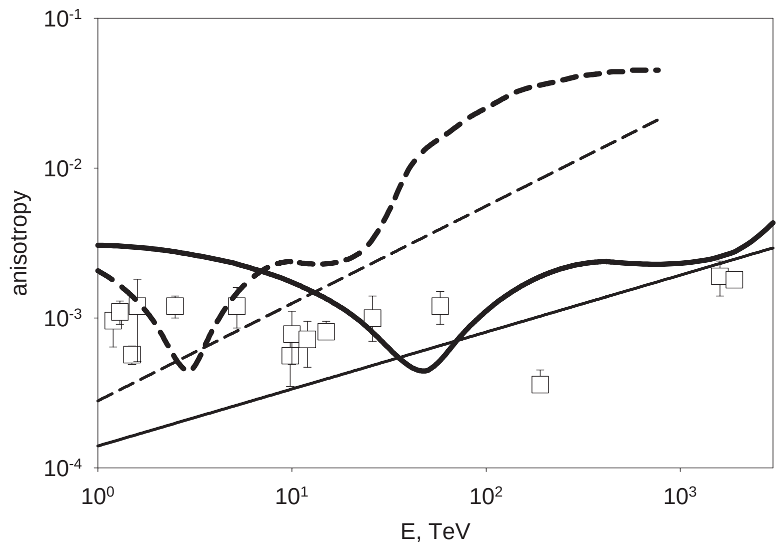

Fig. 1. The CR anisotropy produced by local supernovae (thick curves) and the expected fluctuation anisotropy (thin straight lines) in the reacceleration (solid curves) and the plain diffusion (dashed curves) models. The data on CR anisotropy are taken from [1].

density is maintained by supernovae in the Galactic disk with the rate $\sigma_{SN} = 50$ kpc^{-2}Myr^{-1}. The list of the local SNRs is probably complete for objects with distances from the Earth $r < 1$ kpc and the ages (the light-arrival times) $t < 0.05$ Myr. The following SNRs are included in our calculations: SN 185 ($r = 0.95$ kpc; $t = 1.8 \times 10^{-3}$ Myr), RX J1713.7-3946 ($1; 2 \times 10^{-3}$), S 147 ($0.8; 4.6 \times 10^{-3}$), Cygnus Loop ($0.77; 2 \times 10^{-2}$), G65.3+5.7 ($0.8; 2 \times 10^{-2}$), Vela ($0.25; 1.4 \times 10^{-2}$), HB21 ($0.8; 2.3 \times 10^{-2}$). We do not take into account the very young close remnant RX J0852.0-4622 (0.2 kpc, $t = 0.7 \times 10^{-3}$ Myr) recently discovered in ROSAT data [2]. The inclusion of this source would give the anisotropy that is more than two orders of magnitude larger than the observed one. It well may be that this SNR is at the stage of a free expansion when the accelerating CRs are still confined inside the envelope (it is assumed that CRs are accelerated by the diffusive shock acceleration mechanism). The results of calculations are illustrated in Fig. 1. The main contribution to the anisotropy goes from Vela at $E < 150$ TeV in the reacceleration model, and $E < 6$ TeV in the plain diffusion model. The source S 147 dominates at higher energies up to the knee in the reacceleration model, and up to about 40 TeV in the plain diffusion model where SN 185 and RX J1713.7-3946 lead at higher energies till the knee.

4. Discussion and Conclusion

The results of calculations of the "typical" statistical CR anisotropy in the galactic disk is very different from the calculations where the actual distribution of local SNRs is used, see Fig. 1. The discrepancy between these two approaches is apparently less at high energies. Fig. 1 indicates the inadequacy of the plain diffusion model with a strong dependence of diffusion on energy $D_d \propto E^{0.54}$. The predicted anisotropy exeeds the observed one by more than an order of magnitude at $E > 50$ TeV. The model with distributed reacceleration has a weaker dependence of diffusion on energy $D_a \propto E^{0.3}$ and it is more compatible with the data on anisotropy: the discrepancy is roughly within the factor 3.

It is worth emphasizing the limited accuracy of our model. The assumption of isotropic diffusion is the most questionable. The strong random magnetic field at the main scale makes the diffusion close to isotropic on distances of the order of a few hundred parsecs but not at a short distance where the observed anisotropy is formed. Another critical point is the assumption of instant point sources of the same CR power. In reality the accelerated CRs can be confined inside the SNR for a time from 500 yr for the highest energy particles to 5×10^4 yr for GeV particles, and the kinetic energy of SN ejecta that is the energy reservoir for the CRs production has a considerable dispersion. Also, the large scale gradient of SNR distribution in the Galaxy and the complicated chemical composition of CRs should be taken into account. We plan to improve the calculations in a forthcoming publication.

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5. References

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