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Cosmic Rays in Galactic Diffusion Model with random Supernova Outbursts: Statistical Fluctuations, Anisotropy, Very High Energy Electrons

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The propagation of cosmic rays in the Galaxy with random supernova remnants, the potential sources of cosmic rays, is considered. The data on energy spectra and anisotropy of high energy protons, nuclei and electrons, and the astronomical data on supernova remnants as well as the theoretical results on particle acceleration in supernova remnants and on the nature of interstellar turbulence are used to constrain the value of cosmic ray diffusion coefficient, its dependence on position and energy.

1. Introduction

The SN explosions that give rise to the galactic cosmic rays are essentially statistical events, discrete in space and time. This poses the question as to whether the fluctuations of cosmic ray density and anisotropy are significant [1]. The problem can be approached by an analytical calculation of the average values and their fluctuations in the frameworks of "statistical mechanics of supernovae" [1-3], by a numerical simulation [4-6], and by a calculation of the cosmic ray distribution based on the astronomical information about local SNRs [7-9]. Below we study the effects of cosmic ray fluctuations produced by random SN bursts in the diffusion model of energetic particle transport in the Galaxy with flat cosmic-ray halo. The present study is a continuation of our work [10]. The diffusion model parameters include the scalar diffusion coefficient $D(E)$ and the source distribution $q(E,x,y,t)\delta(z)$ that represents the cosmic ray production by supernova bursts in a thin disk. The coordinate z is perpendicular to the galactic plane. There is a cosmic-ray halo boundaries at $|z| = H$ and $r = R$ where cosmic rays freely exit from the Galaxy. We consider the proton-nucleon and the electron components of very high-energy cosmic rays $E > 0.1$ TeV since the fluctuations are not significant at low energies. Also, the data on cosmic ray anisotropy are not affected by the modulation in the heliosphere at $E > 1$ TeV. At such high energies, one can ignore the ionization energy losses, the nuclear interactions with interstellar gas, and the possible reacceleration on interstellar turbulence.

The diffusion coefficient is well determined at energies 10^{-4} to 10^{-1} Tev/nucleon [11], where the data on secondary nuclei are available. There are two basic versions of the diffusion model that differently explain the observed peaks in the ratios of fluxes of secondary and primary nuclei at energy about 10^{-3} TeV/n. They differ by the values of the diffusion coefficients. Based on results [11], we accept for particles with a charge Z the values $D = 1.55\times(E/Z)^{a}H_5$ kpc^2/Myr, $a = 0.3$ in the model with distributed reacceleration, and $D = 2.76\times(E/Z)^{a}H_5$ kpc^2/Myr, $a = 0.54$ in the plain diffusion model, where E is in TeV and $H = 5H_5$ kpc. It is assumed that the diffusion does not change its character up to 10^5 TeV. The accepted local SN rate in the galactic disk is $\sigma_{\text{sn}} = 50$ kpc^{-2}Myr^{-1}, and each SNR instantly inject $S(E) \sim E^{-\gamma}$ energetic particles in the interstellar space where the source spectrum index is $\gamma = 2.4$ in the model with reacceleration and $\gamma = 2.16$ in the model with no reacceleration so that the observed proton spectrum $\sim E^{-2.7}$ is reproduced in both models. The method of calculations of the average values and dispersions of cosmic ray density and anisotropy was presented in [2,3] where it was applied to the not realistic case of an unbounded 3-D distribution of sources.

2. Statistical fluctuations of Galactic cosmic rays

Using the technique described in [3], one can find the average cosmic ray proton density in the galactic disk $<N> = S\sigma_{\rm sn}H(2D)^{-1} \sim E^{-\gamma-a}$ and the amplitude of "typical" fluctuations

$$\frac{\delta N}{N} \equiv \left\langle (\delta N)^2 \right\rangle^{1/2} \Big/ \langle N \rangle = \frac{D^{1/2}}{(2\pi\sigma_{sn})^{1/2} H^2} \left(\sum_{n,m} - Ei\left(-\left((n-1/2)^2 + (m-1/2)^2 \right) \frac{\pi^2 D\tau}{H^2} \right) \right)^{1/2} \approx$$

$$\frac{1}{2^{3/2}\pi\sigma_{sn}^{1/2} H\tau^{1/2}} \approx \frac{D^{1/4}}{2\pi^{3/4}\sigma_{sn}^{1/4} H} \propto (E/Z)^{a/4}, \;\; \tau = (4\pi\sigma_{\rm sn}D)^{1/2}, \; \tau << H^2/{\rm D}. \qquad (1)$$

Here m, $n = 1,2...$; $Ei(x) = \int_{-\infty}^{x} dt t^{-1} e^{t}$ is the exponential integral; the cutoff parameter τ takes into account the absence of very young and nearby sources [2,3,12], its typical value is estimated as $\tau = (4\pi\sigma_{\rm sn}D)^{-1/2}$.

Eqs. (1) give $\delta N/N = 0.018 \times H_5^{-3/4} E^{0.075}$ in the model with reacceleration, and $\delta N/N = 0.021 \times H_5^{-3/4} E^{0.14}$ in the plain diffusion model. Thus the "typical" fluctuations of proton intensity at the knee are about 3 – 6 %.

The amplitude of anisotropy in the diffusion approximation is $\delta = -3D\nabla N (cN)^{-1}$. The fluctuation anisotropy for protons and nuclei at $\tau << H^2/D$ is equal to

$$\delta_{fl} \approx \frac{3}{2^{5/2}\pi^{1/2} c\sigma_{sn}^{1/2} H\tau} = \frac{3D}{2^{3/2} cH} \propto (E/Z)^{a}, \;\; \tau = (4\pi\sigma_{\rm sn}D)^{1/2}. \qquad (2)$$

In the case of electrons, the energy losses $(dE/dt)_{\rm loss} = -bE^2$ where $b \approx (4.3 \text{ Myr} \times \text{TeV})^{-1}$ at 0.1 to 10 TeV should be taken into account. It leads to rather cumbersome analytical solutions. The approximate solution can be easily found at high energies $E > 0.1$ TeV where the electrons loose their energy before reaching the halo boundaries and the system can be considered as unbounded (the formal condition is $(1-a)bEH^2/D(E) >> 1$). The average density of cosmic ray electrons and its fluctuation are given then by the following equations:

$$\langle N \rangle \approx \frac{2\sigma_{sn} S(E)}{\sqrt{\pi (1-a) bED(E)}} \propto E^{-\gamma - \frac{1+a}{2}}, \;\; \frac{\delta N}{N} \approx \sqrt{\frac{(1-a)bE}{8\pi\sigma_{sn} D(E)\tau}} = \frac{((1-a)bE)^{1/2}}{2(\pi\sigma_{sn} D(E))^{1/4}} \propto E^{\frac{2-a}{4}}. \qquad (3)$$

Eq (3) allows estimating $\delta N/N \approx 0.22E^{0.425}$ in the reacceleration model, and $\delta N/N \approx 0.15E^{0.365}$ in the plain diffusion model. The level of strong fluctuations $\delta N/N = 1/3$ is reached at energies 3 and 9 TeV respectively.

The divergence of Eqs. (1) - (3) at $\tau \rightarrow 0$ is due to the dominance of nearby young SNRs. The knowledge of the properties of local recent SNs is needed to make accurate estimates of cosmic ray fluctuations.

3. Effect of individual supernova remnants

The list of the local SNRs with determined parameters is probably representative for objects with distances from the Earth $r < 1$ kpc and the ages (the light-arrival times) $t < 0.05$ Myr. The following SNRs which belong to this group are included in our calculations: SN 185 ($r = 0.95$ kpc; $t = 1.8 \times 10^{-3}$ Myr), RX J1713.7-3946 (1; 1.6×10^{-3}), S147 (0.8; 4.6×10^{-3}), G114.3+0.3 (0.7; 7.7×10^{-3}), Cygnus Loop (0.77; 2×10^{-2}), G65.3+5.7 (0.8; 2×10^{-2}), Vela (0.3; 1.1×10^{-2}), HB21 (0.8; 2.3×10^{-2}). The young close remnant "Vela Junior" ($r = 0.2$ kpc; $t = 0.7 \times 10^{-3}$ Myr) discovered in ROSAT data [13,14] was not included in the calculations. The inclusion of this SNR would give the anisotropy that is more than two orders of magnitude larger than the observed one. It well may be that the accelerated high-energy particles are still confined inside the envelope of this very young SNR. Also, the distance to the "Vela Junior" is not well determined and it may be as large as 1.5 kpc [15] that would makes this source not important for our consideration.

The results of calculations of cosmic ray anisotropy are presented in Figure. 1 where the effect of global diffusion leakage from the Galaxy, the action of local SNRs, and the "typical" fluctuation anisotropy are shown separately. The radial dependence of the background SNR distribution [16], the yield of local young SNRs listed above, the finite thickness of the galactic disk and the vertical displacement of the Sun position from the galactic plane, and the complicated elemental composition of cosmic rays were taken into account in these calculations. It is assumed that the knee in the observed cosmic ray spectrum arises in the process of particle acceleration in SNRs as in the model [17].

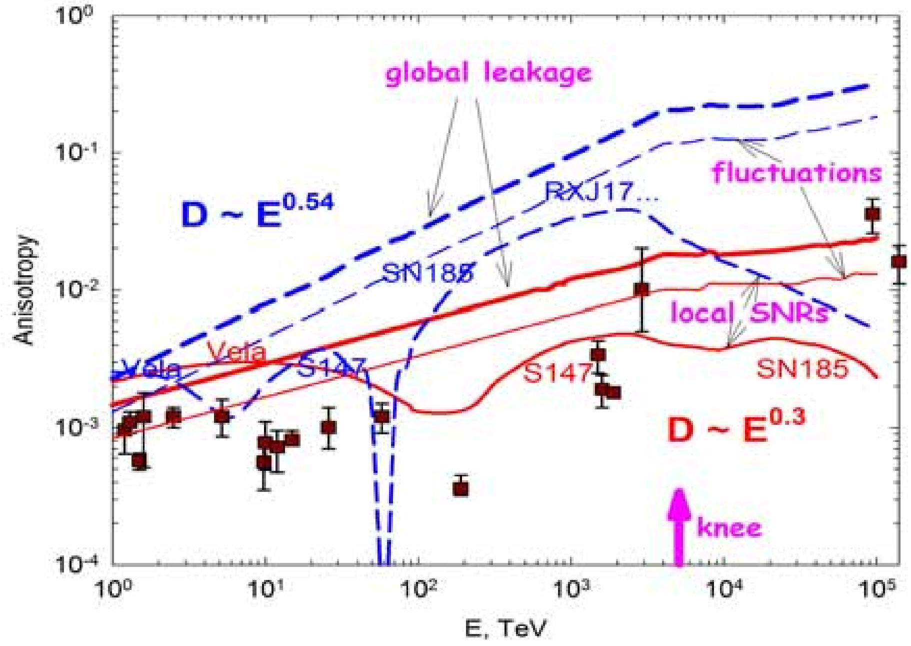

Figure 1. Cosmic ray anisotropy: blue dash lines – plain diffusion, red solid lines – reacceleration model. The data are taken from [18].

Fig. 2 shows the spectra of very high energy electrons calculated with the account of contribution from local galactic SNRs. It is assumed that the maximum energy of electrons at the source is 100 TeV. The procedure of calculation principally follows the approach used in [7,9].

4. Discussion and conclusion

The discrete nature of cosmic ray sources – the SNRs – is important for the interpretation of data on cosmic ray anisotropy and on the spectrum of very high-energy electrons. The diffusion model with reacceleration ($D \sim E^{0.3}$) is bearably compatible with data on cosmic ray anisotropy. The discrepancy between calculated and measured anisotropy is roughly within the factor 3. The plain diffusion model ($D \sim E^{0.54}$) predicts too large anisotropy. The effect of global leakage of cosmic rays from the Galaxy probably dominates at $E > 10$ TeV. The Vela SNR determines the observed cosmic ray anisotropy at 1 - 10 TeV and the flux of very high-energy electrons. It is predicted that the heavy inverse Compton and synchrotron energy losses cause the considerable steepening of electron spectrum at $E > 10$ TeV even if the acceleration works up to higher energies. The reliable determination of distance and age of the "Vela Junior" is quite important for the investigation of cosmic ray acceleration in SNRs and the study of particle transport in the Galaxy.

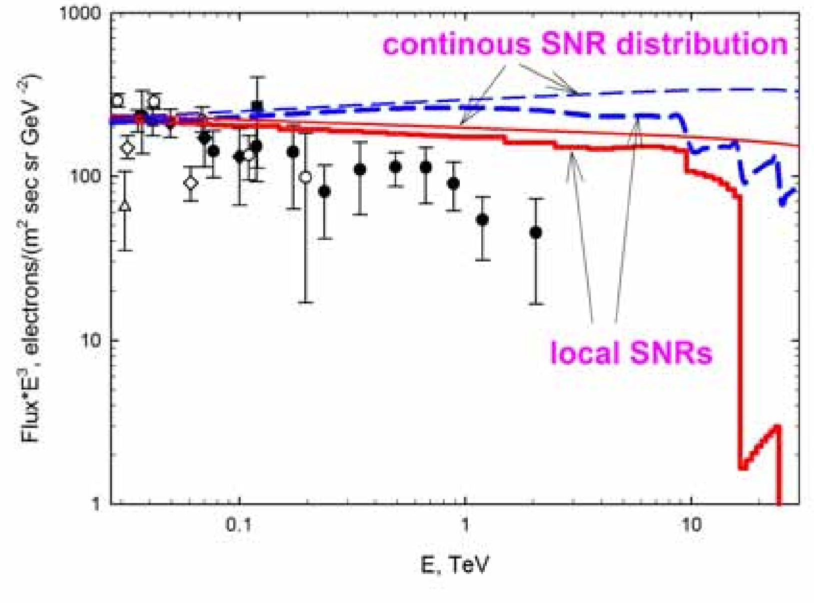

Figure 2. Spectrum of very high-energy electrons. The data are taken from [9].

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