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On probable contribution of nearby sources to anisotropy and spectrum of cosmic rays at TeV-PeV-energies

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Abstract: Anisotropy as well as a fine structure of cosmic ray spectra is very sensitive to a contribution of young nearby SNRs and we investigate these contributions by simultaneous analysis within the fixed sample of hypothetical nearby sources. All the sources are divided into 2 groups: actual nearby young sources selected from the last gamma astronomy catalogs and other sources which are distributed randomly within the Galactic disk with a birth-rate about 1/50 yr. The arm structure of source distribution throughout the galactic disc, a time dependence of accelerated protons during shell evolution were taken into account as well as the experimental procedure of “two-dimensional” anisotropy measurements. We succeeded in description of anisotropy up to 10^{18} eV using only the following assumptions: the rigidity dependent E_{max} for SNIa remnants that give the main contribution to the knee region, and the absence of very close source (R<500 pc, T<100 kyr) with clear shell structure. Neither a “single source” nor a sharp cutoff of the source spectrum explain the distinctive “Iron-bump”, observed in GAMMA and TUNKA experiments. Only introduction of a narrow “bump” in the source spectrum of young SN Ia remnants may explain it.

Keywords: Dipole anisotropy, origin of the knee, cosmic ray spectrum.

1 Introduction

A knowledge of actual nearby sources is crucial for interpretation of experimental data on cosmic ray (CR) anisotropy [1], high (~ TeV) energy electrons [2] and fine structure of spectrum at PeV energies [3,4]. The goal of our work is to investigate these problems, taking into account a stochastic nature of CR sources. All sources are divided into 2 groups: actual nearby young sources selected from gamma - astronomical catalogs and other sources which are distributed randomly in the Galactic disk. In the previous work [5] we calculated and analyzed the CR electron spectrum simultaneously with CR proton anisotropy at 100 GeV-100 TeV, assuming that electrons and protons are accelerated in the same shell supernovae and all Galactic sources are identical. No indications of nearby unidentified sources were found. But data on anisotropy imposed a limitation on a contribution of the Vela X remnant: it produces several times less CRs than an average shell in the Galaxy.

The remarkable fine structure of all particle spectra above the knee was found in Tunka-133 [6], KASCADE Grande [8,9], Gamma [10] experiments. It consists in a “hardening” around $2x10^{16}$ eV and narrow “bump” around 10^{17} eV. In the present paper we extend our model [5] to higher energies and calculate the fine structure of all particle spectra and anisotropy around the knee paying special attention to the possible contribution of nearby sources.

2 Method of calculation

2.1 Semi-statistical approach

To calculate a flux and anisotropy of cosmic rays near the Earth we use a semi-statistical approach [1-3]: all sources are divided in 2 groups. Selected from gamma astronomy catalogs, the first group contains real nearby young sources, which are located within a distance R_{near} around the Earth and have ages less than T_{near}. Sources of the second group are distributed randomly in time (with a birth rate 1/50 yr) and space (with account for the arm structure of Galaxy). The values R_{near} ~1.5 kpc T_{near} ~ 10^5 yr are chosen to provide a completeness of the sample, more old sources are missing, because their shells have dissolved.

We use a simple flat-halo Galaxy model of cosmic ray transport with halo boundaries at $|Hz| = 4$ kpc and Rg= 15 kpc, the particle propagation is described in terms of Green's functions [1], so that CR density and anisotropy at the Earth are calculated as a sum of individual contributions from N sources located at distances r_i, and emitted the spectrum $Q_i(E, E_{\max})$ t_i years ago – $F=\Sigma\, G(t_i, \mathbf{r_i}, E)$:

$$\mathrm{G_i}\ (\mathrm{t_i}, \mathrm{r_i}, \mathrm{E}) = Q_i(E, E_{\max}) \frac{\exp\left(-\dfrac{(r_i)^2}{4R_{id}^2}\right)}{4\pi H \cdot R_{id}^2} \times S_i$$

$$Si = \sum_{n=1}^{\infty} \exp\left(-\frac{(2n-1)^2 \pi^2 R_{id}^2}{4H^2}\right)$$

Factor S_i takes into account the halo boundaries (at $H << Rg$). A diffusion radius $R_{id}=(D(E)\cdot t_i)^{1/2}$ depends on energy through diffusion coefficient $D=3.3\times10^{28}\, E^{0.33}$ cm^2/s m chosen in accordance with GALPROP (model with reacceleration).

2.2 Nearby sources

Observations of high energy photons in principal provide a direct view of the astrophysical accelerators of charged particles. But time of observation for gamma-rays and cosmic rays is shifted. This shift is ~ 10^4 yr at PeV energies and ~ 10^5 yr at TeV energies for sources located at 1 kpc that is comparable with the life time of SNR shell and PWN. At such late stage of evolution, T≈10^5 yr, the envelope disperses in ISM and a core collapsed SN can be seen only as pulsar or PWN. Taking this fact into account we compiled a list of nearest sources from the following catalogs: catalog of 274 SNRs, including 174 SNRs with measured distances [11]; catalog of 54 PWNe [12]; Fermi-LAT catalog of 46 gamma-pulsars [13]; ATNF catalog of 1827 pulsars; catalog of TeV sources of HESS [14].

The total number of selected gamma ray sources with somehow determined ages and distances is 73, and 25 sources are inside the circle $r_i < R_{near} = 1..5$ kpc with age $t_i < T_{near} = 10^5$ yr, see [5]. Among 25 sources 6 SNRs have no pulsar or PWN, so they may be of SNIa type, other 19 sources can be considered as core collapse SNe because they have or gamma-pulsar (11) or PWN (11) or radio-pulsar (8). Among these 19 sources radio shells are found only in 12 objects. Other 7 sources probably have ages ~ 10^5 yr and their envelopes are dispersed in ISM, also in some cases envelopes might have been not produced at all. TeV - emission is observed only in one shell SNR J1713-3946 and in 6 core collapse SNe. To be sure that our sample of nearest sources is complete, we estimated the expected number of sources with distance $R<1.5$ kpc and age $T<10^5$ y, N_{exp}. assuming the SNe rate 1/50 yr and accounting for the arm structure we get: Nexp = 10 for $R_{near} < 1.0$ kpc and $T_{near} < 10^5$ y; $N_{exp} = 24$ for $R<1.5$. The expected number coincides well with the found numberl.

2.3 Method of anisotropy calculation

We calculated anisotropy amplitude and direction α (right ascension) in the approximation of isotropic diffusion. The x- component of anisotropy is [1]:

$A_x(E, \mathbf{r}, t) =$

$\sum_{i=1,\, Nr} (3{*}D/c)\, \partial/\partial x(G(t_i, \mathbf{r_i}, E)) / F(E)$

We take into account the experimental procedure of "two dimensional" measurement [15, 16] of sidereal day variation, calculated as variation $\varepsilon(\alpha, \delta)$ of counting rate $n(\alpha, \delta)$ as a function of α relative to the average counting rate at fixed declination δ - $<n(\delta)>$ [15] :

$$\varepsilon(\alpha, \delta) = (n(\alpha, \delta) - <n(\delta)>) / <n(\delta)>$$

We fixed the grid of declinations (with 10^o strip) and right ascension (with Δα= 1 hour strip). For every cell (α_k , δ_k) characterized by vector $\mathbf{r}_k$ we calculated the projection of flux gradient produced by i-source with equatorial coordinate α_i, δ_i, on the vector $\mathbf{r}_k$. Next we averaged $\boldsymbol{\varepsilon}$ (E, t, α_k , δ_k) over α_k in the bands with fixed declination δ_k, summed up over all N sources and divided by total F(E). Thus we got the relative variations of counting rate $\boldsymbol{\varepsilon}$ (E, $\mathbf{r}$, t, α_k , δ_k) with α_k , δ_k, analogous to experimental variations. In all cases of calculations a pure dipole anisotropy with maximum to celestial equator (δ_k =0) and the same $\alpha_k^{\max}$ for all observation bands of δ_k was found.

2.4 Model of the knee

One needs to adopt some model of the knee to calculate the energy dependence of anisotropy at high energies. Two points are important here. First, the anisotropy at some energy E depends on the density of sources [2] which can accelerate particles up to this energy and on the particle charge Z (through diffusion coefficient D (Eo/Z)). Second, the primary nuclei give a significant contribution to the measured anisotropy at energies higher than several tens of TeV where only EAS data can be used. It is in contrast to lower energy measurements of anisotropy where the muon component mainly produced by primary protons is used.

The cosmic ray acceleration and the evolution of a supernova blast wave were studied In [17] with the use of the numerical code that includes the hydrodynamic equations solved together with the diffusion–convection transport equation for the cosmic-ray distribution function. It was shown that the maximum particle energy E_{max} depends on a number of parameters and E_{max} differs for different types of supernovae: E_{max}~4×Z PeV for SNIa, 1 ×Z PeV for SNIb/c, 0.1×Z PeV for SN IIp, (300-600)×Z PeV for Type IIb SN. The parameters of SNRIa have small dispersion and its E_{max} is well fixed. Other SNe demonstrate a great variety of their properties. The continues distributions of sources in space and time was assumed in [17]. The model [17] reproduces well the general shape of all particle spectrum up to more than 10^{18} eV including the knee feature.

We employ results of [17] but with discrete sources divided into two groups (see Section 2.1 2.2) and assuming the randomly distributed E_{max} for SNIIp and SNIbc in interval 1 TeV - 4000 TeV: : 30% among all SNR (1 TeV<E_{max} <10 TeV), 20% (10 TeV<E_{max} <100 TeV),20%

(100 TeV<E_{max} <4000 TeV); 20 % (SNRIa) have E_{max} ~ 4 PeV with small dispersion. 5 % of all SNR have E_{max} ~ 6× 10^{17} eV. This suggestion leads to more steep total CR spectrum by dγ~0.17 in comparison with the source spectrum. γ_{source}=2.2 was chosen in accordance with [17]. The expected observed spectrum in this case is $\gamma_{obs} = \gamma_{source} + d\gamma + d\gamma_{prop} = 2.7$ where $d\gamma_{prop} = 0.33$ is a steepening caused by propagation in the Galaxy.

The chemical abundance of 5 groups of nuclei around the knee is closes to "normal" : 37% of H, 35% of He, 8% CNO, 10 % of intermediate nuclei, 10% of Fe.

3 Results of calculation

3.1 Anisotropy

Fig. 1 we presents the data on amplitude (upper panel) and right ascension (lower panel) obtained in muon experiments up to 20 TeV and in EAS experiment above 20 TeV (compilations from [16],[9]).

The most uncertain question, we confronted with: are there SNRs being able to accelerate to 4 PeV among our list of nearby sources? Of cause, we include J1713-3946, and Vela Junior (G266.2-1.2) , 1006, because there are theoretical predictions of PeV-maximal energy for them, but all of them are further or around 1 kpc from us. The very unusual gamma ray source seen in all energy ranges up to 10 TeV is Vela X (G263.9-3.3) SNR + PWN(RX J0852.0-4622), and in that time being closest (R= 290 pc, T~11ky), can contribute significantly to observed CR flux, but the amplitude and α are in direct contradiction with experimental data [5]. We concluded in [5] that the contribution of Vela X to CR flux is not more than 10% of an average SNR in the Galaxy. It is also supported by the significant difference of it's shell (with clumps and complex outer boundary) with the shells like RX J1713.7-3946, 1006, being classical for the CR acceleration on the blast wave. All other shell SNR have a distance 0.56 - 0.8 kpc: (Cygnus loop, HB9, HB21, S147) and age 7- 40 kyr (that is a needed time for cosmic rays of 10^{13}-10^{15} eV to reach the Earth), and they can be considered as potential contributors to the knee region. They are too old to be registered in a few TeV gamma-rays, because according to [18] 10 TeV protons (and ~1 TeV gamma) are most probably produced at the age ~10 kyr.

Below we considered two extreme cases: *A*- absence of CR sources with E_{max}~ 4 PeV within R<1 kpc; *B* – 4 shell SNRs (Cygnus loop, HB9, HB21, S147) accelerate CR up to 4 PeV. The estimated total contribution of nearby sources at 4 PeV is ~ 5 % *in A* and 30% in *B cases*s. Also we present in Fig. 1 and 2 some intermediate cases when one of the enumerated SNRs accelerate CR up to 4 PeV.

Amplitude and direction of dipole component of anisotropy, calculated in cases *A* and *B* are presented in Fig. 1. We stress that both cases are not in contradiction with experiment due to two main factors: a) the increase of heavy nuclei abundance leads to decrease of diffusion coefficient at a given energy per particle; b) absence of very close source (*R<500* pc, *T<10^5* yr) with clear shell structure small ejected mass (similar to SNR Ia) that would be able to accelerate CR up to 4 PeV. The enumerated SNRs are probably not type Ia supernovae and they were not able to accelerate up to 4 PeV in the past (Cygnus Loop has too high ejected mass 12-15 Mo, HB21 is an evolved of mixed-morphology SNRs in radiative stage can be too old, HB9, R5, S147 are possibly associated with pulsars). So, the case *B* probably gives an upper limit of anisotropy, but even in this case the contribution of nearby sources is very modest. Only a very young and close source, such as Vela Jr. if it has R~0.3 kpc, T=0.7 Kyr (see Fig. 1) can imitate the knee. However it would obviously contradict measured anisotropy.

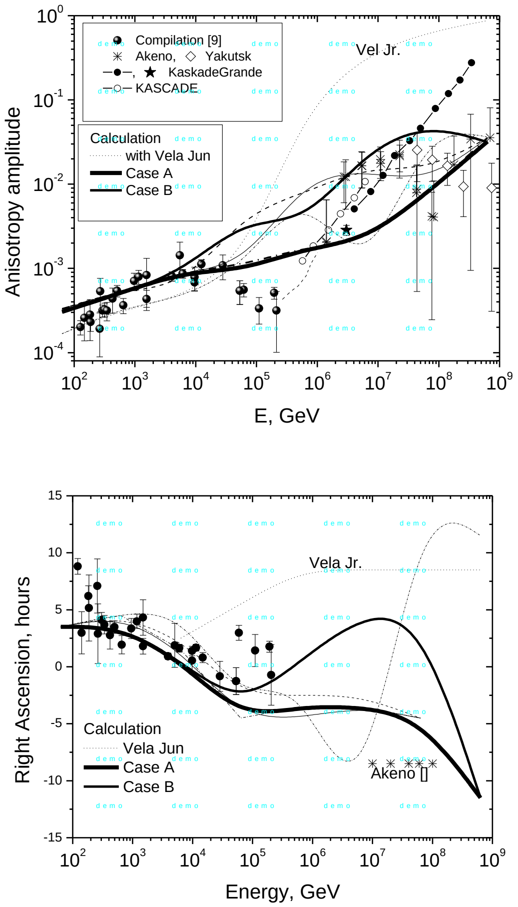

Figure. 1. Amplitude and right ascension of anisotropy at TeV-PeV energies. Data compilations are taken from [9] and [16]). Cases *A* and *B* are shown by thick line and thin lines correspondingly. Dash and dash-dotted lines illustrate some intermediate cases. Dotted line corresponds to the case of Vela Jr. with R=0.3 kpc, t=0.7 kyr.

3.2 Fine structure of all particle spectrum

Let us study irregularities of cosmic ray spectrum that are expected in our model of close CR sources. The fine structure around the knee was observed in the latest experiments [7,8,10] and interpreted as a confirmation of the "single source" model [3,4].

In Fig. 2 we show the fine structure of all particle spectrum through the function Str=F(E)/AE^3-1 as it was done in [8]. Our analysis shows that for the explanation of 1st knee, "hardening", and 2nd knee, the most important assumption is a cutoff of source spectra in SNIa remnants: slope at Emax should be changed from 2.2 to 5 or more. At the same time the presence (*Case B*) or absence (*Case A*) of nearby sources able to accelerate up to 4 PeV is not so important (if Vela Jr has parameters R=0.3, T=0.7 kyr, it can change the structure, but this assumption sharply contradicts the anisotropy data, as it is seen in Fig.1).

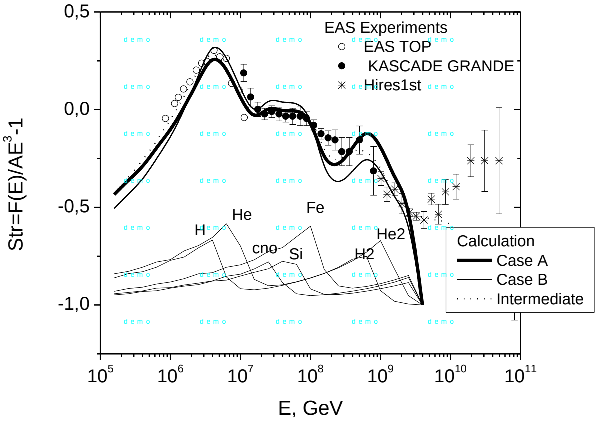

Fig. 2. Structure of all particle spectrum. Experimental points: KASCADE GRANDE [8], Eas TOP. Our calculations: *A, B* and intermediate cases as in Fig.1.The contribution of different nuclei from SNIa and SNIIb (H2,He2) is shown (see text)

Chemical composition play the noticeable part in the structure also: proton and helium nuclei should have nearly equal abundances at ~ 4 PeV; at the same time the amount of Fe nuclei should be not less than 1/3 of He nuclei; the sharp break around 10^{17} eV marks the transition to the contribution of rare SNIIb with Emax~ 6x10^{17} eV and if we exclude SNIIb we can not describe the flat spectrum above 10^{16} eV. The presence of heavy nuclei seems to be excluded in SNIIb sources since it contradicts to the "light" composition observed at 10^{18} in Auger and HiRes experiments.

At least in two recent experiments Tunka 133 [6] and Gamma [10] the very distinctive "bump" (Fig. 3) was detected at energy exactly coinciding with position of Fe-peak, ~ 10^{17} eV (see Fig. 2). Neither a single source nor a sharp cutoff in the source spectrum can explain this bump. Only the introduction of the "bump" with a relative increase of intensity by two times over the dlgE~0.2 before E_{max} into the source spectrum can reproduce the narrow bump in data around 10^{17} eV, see Fig. 3. But in this case the main knee falls to the P and He bumps. Assuming the increase of intensity over the energy range dlgE~0.4 before E_{max} we get more or less satisfactory description of the both structures: the main knee and the bump at 10^{17} eV. Besides, this variant of calculations reproduces well the new data on mass composition in energy range 2 10^{15}- 3 10^{17} eV obtained in experiment Tunka-133 [19]: around 10^{17} eV <lnA> reaches ~3.4+-0.2, and above decreases sharply. The nature of the bump in source spectrum is not clear at all. It might somehow reflect the time dependent emissions of CR from a SNR [18] when the most energetic particles are emitted at the early stage of remnant evolution.

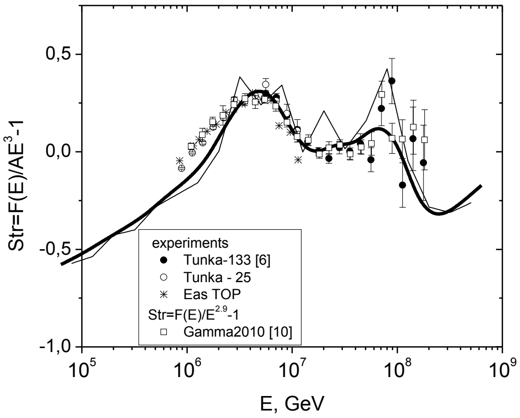

Fig. 3. Structure of all particle spectrum, obtained in experiments Tunka 133 [6] and Gamma [10](GAMMA data is presented as Str=F(E)/AE$^{2.9}$-1). Calculations corresponds to *A case*, but with a "bump" in the source spectrum of SNIa: relative increase of intensity by two times over the dlgE~0.2 before E_{max} (thin line) and dlgE~0.5 (thick line).

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[1] V.S. Berezinskii et al.: 1990. Astrophysics of Cosmic Rays, North-Holland, Amsterdam.

[2]V.S. Ptuskin, F.C. Jones, E.S. Seo. Adv. In Sp. Research. 2006, 37, 1909.

[3] Erlykin A.D., Wolfendale A.W., 1997, J. Phys. G: Nucl. Part. Phys., 23, 979

[4] A.Erlykin, A. Wolfendale,R.Martirosov, CERN-Courier, Jan/Feb, 201,21.

[5] L.G. Sveshnikova, V.S. Ptuskin, O.N. Strelnikova Bull. of the Russian Academy of Sciences. Phys. 2011, 75, 3, pp. 334

[6] Kuznichev L.A.Tunka-133:the new EAS Cherenkov Light Array for Cosmic Ray Study. Proc. of 25th Simp. on Relativistic Astroph., Heidelberg, 2010.

[8] J.C. Arteaga-Velrazquez, W.D. Apel, K. Bekk et al. arXiv:1009.4716v1 [astro-ph.HE]

[9] S. Overe, M. St¨umpertc, W.D. Apela et al. Proc. of the 30th ICRC, Mexico, 2008, Vol. 4 , pages 223–226.

[10]R.Martirosov,A.Garyaka,etal.arXiv:1010.6260[astro-ph.HE],and
http://tunka.sinp.msu.ru/en/presentation/Martirosov.pdf

[11]G.Case,Bhattacharya.A&ASup.1996.Ser.120, 437

[12]O.Kargaltsev, G. G. Pavlov. Astro-ph/0801.2602v2

.[13]A.A. Abdo et al Astro-ph/0910.1608v1

[15] G.Guillian et al. astro-ph/0508468v4, 2008.

[16] Amenomori M et al. Astro-ph/ 0505114v1. 2005.

[17]V.Ptuskin, V.Zirakashvili ... Astroph. J. 2010. 718,31

[18]] Ptuskin, V.S. & Zirakashvili, V.N. 2005, A&A, 429, 755

[19]L.A.Kuzmichev. Moscow workshop "Large Scale Experiments..",.2011,May,16-18.
http://tunka.sinp.msu.ru/en/presentation/Kuzmichev.pdf