Anisotropy analysis of EAS data in the knee region

S. V. Ter-Antonyan

Yerevan Physics Institute, 2 Alikhanian Br. Str., 375036 Yerevan, Armenia

Abstract. Based on MAKET-ANI EAS data the distributions of equatorial coordinates of EAS core directions are obtained in the knee region. Anisotropy of primary cosmic rays is displayed only by declination equatorial coordinates ($\delta_a \simeq 20^0 \pm 3^0$) at primary energies more than 5-10 PeV. The fraction of anisotropic component turns out $\sim 10\%$ in the knee region.

1 Introduction

The behavior of EAS size spectra in the knee region points out a possibility of a multi-component nature of the primary nuclear flux (Linsley, 1983; Gaisser and Stanev, 1993; Biermann, 1993; Stanev et al., 1993; Erlykin and Wolfendale, 1997; Ter-Antonyan and Haroyan, 2000). As follows from (Stanev et al., 1993; Ter-Antonyan and Haroyan, 2000; Ter-Antonyan and Biermann, 2001), the best description of EAS size spectra in the knee region may be achieved providing at least two components in the primary cosmic ray flux. Confirmation of the multi-component origin of cosmic rays can be obtain by investigations of distribution of EAS arrival directions. Especially, it is interesting to measure of the anisotropy in the vicinity of the knee region ($10^{15} - 10^{16}$ eV) where the accuracies of EAS experiments in last years have significantly increased.

In this paper, based on MAKET-ANI (Chilingaryan et al., 1999) EAS data ($\sim 10^6$ events with $N_e > 10^5$) the equatorial coordinate distribution of EAS arrival directions are investigated. Violations of isotropy ($\sim 5 - 10\%$) are obtained at energies $E > 10$ PeV.

2 EAS anisotropy

Principal complications of the investigation of the EAS anisotropy are:

Correspondence to: samvel@jerewan1.yerphi.am

1. EAS attenuation in the atmosphere (the intensity of shower size $F(N_e, \theta)$ strongly depends on a zenith angle of incidence (θ) at the given observation level);

2. dependence of the EAS size on the energy (E) and primary nucleus (A);

3. interruptions of exposition local time, which are inevitable in EAS experiments.

Factors 1-3 do not allow in principle to apply the traditional (on-off) methods of measuring the cosmic ray anisotropy and here, a simulation method is applied taking into account above factors in the frameworks of QGSJET interaction model (Kalmykov and Ostapchenko, 1993) and predictions of the 2-component origin of cosmic rays (Biermann, 1993). The test of this models by modern EAS size spectra at different zenith angles and different observation levels one can find in papers (Ter-Antonyan and Haroyan, 2000; Ter-Antonyan and Biermann, 2001).

Assume that the primary nuclear flux $I(E)$ consists of isotropic $I_0(E)$ and anisotropic $\Im(E)$ components (Berezinsky et al., 1984)

$$I(E) = I_0(E) + \Im(E, \alpha_a, \delta_a) \quad , \qquad (1)$$

where α_a, δ_a are equatorial coordinates of anisotropic direction. Let also the factor of anisotropy $\varepsilon = \Im(E)/I(E)$ is small ($\varepsilon \ll 1$) and does not distort the EAS zenith angular distribution due to the Earth rotation and independence of EAS attenuation on the azimuthal angle of incidence (φ).

Then, providing each detected EAS event from $I(E)$ flux with horizontal coordinates θ, φ and local time $\boldsymbol{T}$ by adequate simulated event but from isotropic $I_0(E)$ flux with corresponding coordinates θ^*, φ^* and the same $\boldsymbol{T}$ one can compare (after transformation $\theta, \varphi, \boldsymbol{T}$ and $\theta^*, \varphi^*, \boldsymbol{T} \Rightarrow \alpha, \delta$ and α^*, δ^*) the obtained equatorial coordinate distributions of real EAS data and isotropic simulated data. Evidently, if the anisotropic part of intensity $\Im(E, \alpha_a, \delta_a) = 0$ then the distribution obtained from the experiment must overlap with
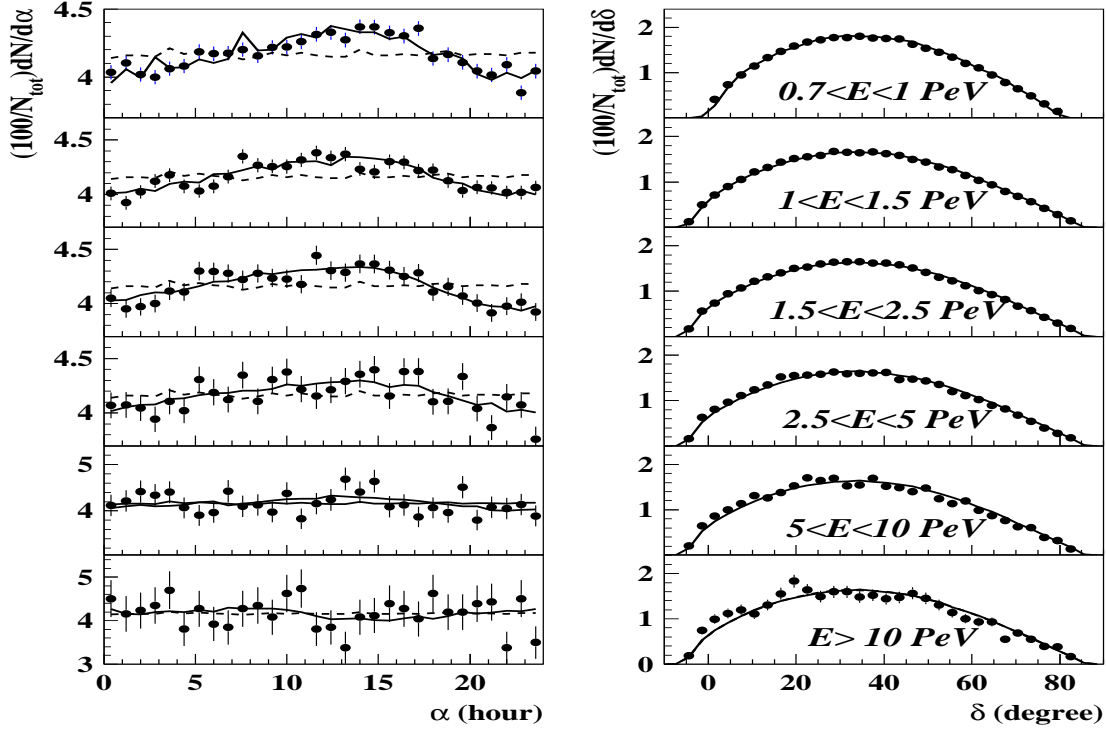
Fig. 1. Equatorial coordinate distributions of all showers at different primary energies (E). Symbols are the Maket-ANI data. Solid lines are the expected distributions obtained by simulations of the isotropic primary component (off-component) taking into account the local time of each detected EAS event. Dashed lines are the isotropic components at the uniform local time distribution of each EAS detected event.

the simulated one. Any considerable discrepancies (out of statistical errors) will point out to the existence of anisotropy. The presented method completely solves the problems 1 and 3, however, the same normalization of real and simulated distributions (due to a flux $\Im(E, \alpha_a, \delta_a)$ is unknown) does not give a direct possibility to determine the absolute intensity of the anisotropic component.

Taking the above into account, each detected EAS event is characterized by a 9-dimensional vector $\boldsymbol{D}(E, \theta, \varphi, \boldsymbol{T}(y, m, d, h, u, s))$, where $E \equiv E(N_e, \theta)$ is the evaluation of a primary energy on the basis of the measured EAS size N_e and zenith angle θ, $\boldsymbol{T}(y, m, d, h, u, e)$ is a local time vector with components y -year, m -month, d -day, h -hour, u -minute, e -second of a detected event. Here we used the vector definition only for briefness and convenience.

The estimation of the primary energy E by the measured EAS size N_e is performed by inverse interpolation of function $\overline{N_e} \equiv \overline{N_e}(E, \overline{A}, \theta)$ at average primary nucleus $\overline{A}(E) = \exp(\overline{\ln A})$. $\overline{A}$ values are determined by 2-component primary spectra (Biermann, 1993). A tabulated function $\overline{N_e}(E, A, \theta)$ at given E, A, θ parameters of a primary nucleus was pre-

liminary calculated by means of EAS simulation using the CORSIKA code (Heck et al., 1998) at QGSJET interaction model (Kalmykov and Ostapchenko, 1993). Some details of this simulation one can find in the paper (Ter-Antonyan and Haroyan, 2000). Statistical errors did not exceed $3 - 5\%$ and the high altitude location (700g/cm^2) of the ANI experiment (Chilingaryan et al., 1999) allowed to obtain $\Delta E < 20\%$.

Because the exposition time of the MAKET-ANI array is not continuous and the EAS zenith angular distribution does not adequate to the angular distribution of primary nuclei (factors 1,3 above), we created $i = 1, \ldots, m$ simulated 9-dimensional vectors $\boldsymbol{R}_i(E_i^*, \theta_i^*, \varphi_i^*, \boldsymbol{T})$ for each detected vector $\boldsymbol{D}$ which differ from $\boldsymbol{D}$ only by simulated primary energy (E^*), zenith (θ^*) and azimuth (φ^*) angles. The values of angles θ^* and φ^* are simulated according to distributions: $dF/d\cos\theta = \cos\theta$ and $d\Phi/d\varphi = 1/2\pi$ respectively. The energy (E^*) of simulated events is obtained from 2-component primary energy spectra (Biermann, 1993; Ter-Antonyan and Biermann, 2001) at additional condition of detected events $N_e^*(E^*, A^*, \theta^*) > 10^5$.

Transformation of $\boldsymbol{D}$ and $\boldsymbol{R}_i$ vectors to simple 3-dimensional vectors $\boldsymbol{d}(E, \alpha, \delta)$ and $\boldsymbol{r}_i(E^*, \alpha^*, \delta^*)$ with α -right ascension and δ -declination equatorial coordinates are performed
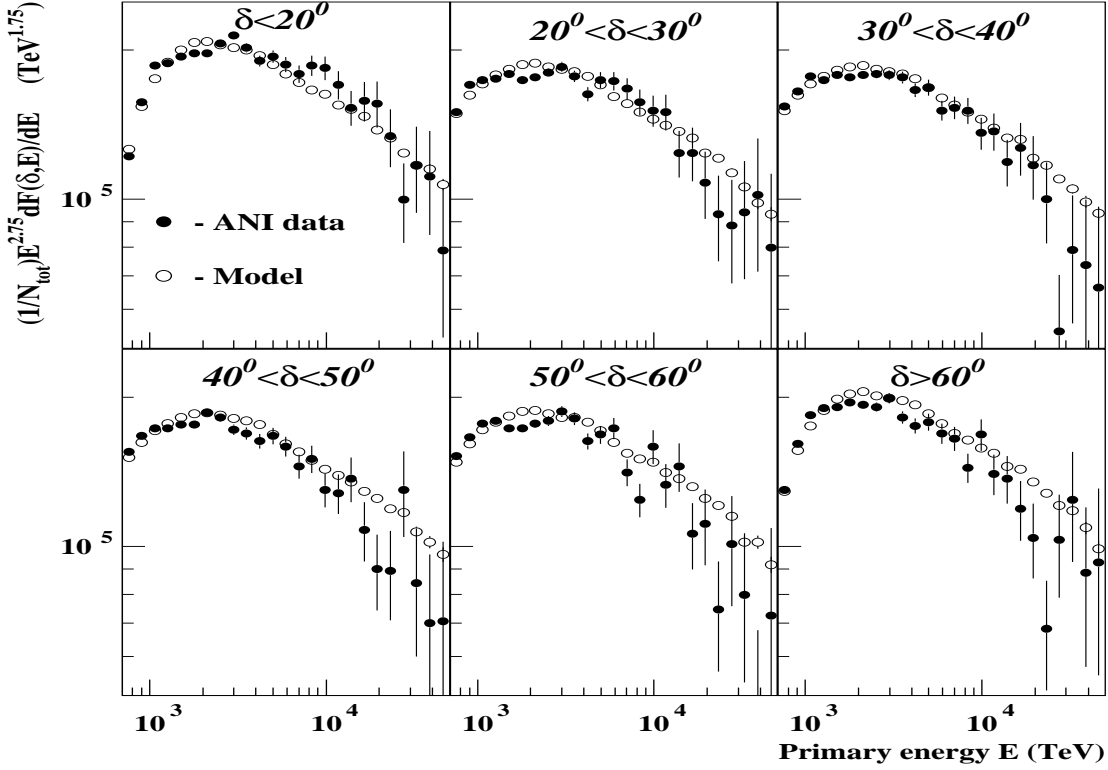
Fig. 2. Detected normalized all-particle primary energy spectra at different equatorial declination δ-coordinates. Black symbols correspond to ANI EAS data. Open circles are the expected energy spectra of an isotropic component (off-component) according to (Biermann, 1993) model.

by astronomical soft (Super-Kamiokande, 1999).

3 Results

The results of investigation of the EAS anisotropy in the knee region by ANI EAS data are shown in Fig. 1,2. Equatorial coordinate distributions $dN/d\alpha$ and $dN/d\delta$ of all showers ($N_{tot} = 10^6$ events at $N_e > 10^5$) at six primary energy (E) intervals are given in Fig. 1. Symbols are the Maket-ANI data $dN/d\alpha$ and $dN/d\delta$ in terms of $(100/N_{tot})$. Solid lines are the expected adequate distributions $dN/d\alpha^*$ and $dN/d\delta^*$ obtained by simulations of isotropic primary component (off-component). Local times T of simulated events and detected EAS events are equal. The total number of events is the same ($N_{tot} = N_{tot}^*$). Dashed lines reflect the expected behavior of the isotropic component at an uniform local time distribution of each EAS detected event.

It is seen, that the distribution of a δ-coordinate at all primary energies is practically independent on a local time distribution. Moreover, a good agreement of expected and detected distributions for equatorial α-coordinate is observed in the

energy range $E > 0.7$ PeV.

However, the discrepancies of detected and expected distributions of the equatorial δ-coordinate increase with the energy. Strong disagreement is observed at $E > 10$ PeV and $\delta \simeq 20^0$. It is necessary to note, that the real disagreement is a little larger than it is seen in Fig. 1 because EAS and simulated data have the same normalizations. Further investigations of the δ-coordinate distribution are given in Fig. 2 where detected normalized all-particle primary energy spectra at different declinations (δ) are presented. Black symbols are ANI data. The open circles are expected energy spectra of isotropical simulated components (off - component) with 50 times higher statistics ($N_{tot}^* = 5 \cdot 10^7$).

Spectral shape in $E < 1 - 2$ PeV range for all declination intervals is determined by the lower limit of the detected EAS size ($N_e > 10^5$). However, the observed fine structure of all-particle spectra at $E > 2$ PeV and declinations $\delta < 30^0$ and $50 < \delta < 60$ can hardly be explained by trivial statistical fluctuations. All data in Fig. 1,2 are obtained in the framework of QGSJET interaction model (Kalmykov and Ostapchenko, 1993) and the 2-component origin of cosmic rays (Biermann, 1993; Ter-Antonyan and Biermann, 2001).

4 Conclusion

From above analysis it follows that there is a partial anisotropic flux with a declination coordinate equal to $\delta_a = 20^0 \pm 3^0$ at primary energies $E > 10$ PeV. The distribution of equatorial α-coordinates agrees with the hypothesis of the isotropic distributions of cosmic rays.

It is interesting to note, that the nearest neutron stars PSR0950 and PSR1133 disposed at $l \simeq 30 - 100$ ps distance from the Earth have declination coordinates $\delta = 30.6^0$ and $\delta = 27.45^0$ respectively. These values are close to the results obtained here ($\delta_a \sim 20^0$). Are these neutron stars a reason of anisotropic flux or not can be elucidated only with significantly large EAS statistics.

References

Berezinsky V.S., Bulanov S.V., Ginzburg V.L., "Cosmic ray astrophysics", Izd. Nauka, Moscow, (1984) (in Russion).

Biermann P.L.: Astron. Astrophys. **271** (1993) 649./
Preprint MPIfR, Bonn, No 700 (1996) 6.

Chilingaryan A. et al., Proc. 26th ICRC, Salt Lake City, **1** (1999) 240.

Chilingaryan A.A. et al., Nucl.Phys. B (Proc.Suppl), 52B (1997) 237.

Erlykin A.D., Wolfendale A.W., Astropart. Phys. 7 (1997) 1./
Astropart. Phys. 7 (1997) 203.
Astropart. Phys. 8 (1998) 265.

Gaisser T.K. and Stanev T., Proc. 22nd ICRC, Dublin (1991).

Heck D., Knapp J., Capdevielle J.N., Schatz G., Thouw T., Forschungszentrum Karlsruhe Report, FZKA 6019 (1998) 90p.

Kalmykov N.N., Ostapchenko S.S., Yad. Fiz. **56** (1993) 105.

Linsley J., Proc. 18th ICRC, Bangalore (1983) **12**, 135.

Stanev T., Biermann P.L., Gaisser T.K., Astrophys. **274** (1993) 902.

Super-Kamiokande collaboration, 1999, http:// www.phys. washington. edu / young/superk/coordinates/

Ter-Antonyan S.V. and Biermann P.L., 27th ICRC, Hamburg (2001).

Ter-Antonyan S.V, and Haroyan L.S., Preprint, arXiv:hep-ex/0003006.