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Anomalous extensive air showers of ultrahigh energy cosmic rays and their relation to pulsars

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Abstract. Extensive air showers of cosmic rays with energies above 8×10^{18} eV registered at the Yakutsk array for 1974 - 1998 have been analyzed. The existence of showers without muons and poor muons are found. Two clusters consisting of the showers without muons are shown.

1 Introduction

According to theoretical calculations (Maze and Zawadski, 1960) the anomalous small number of nuclear active particles and muons of the primary γ-quanta is expected. When γ-quanta have energy 10^{15} eV the expected muon flux density with energy above 10 GeV at a distance r of the shower axis $\rho_\mu^\gamma(r)$ will be less than 1/30 of the muon flux density $\rho_\mu^{Zp}(r)$ of usual showers formed by the protons (p) and nuclei (Zp) (Khristiansen et al., 1975):

$$\rho_\mu^\gamma(r)/\rho_\mu^{Zp}(r) < 1/30. \tag{1}$$

By the Moscow State University extensive air showers (EAS) array data at the energy $E \sim 6 \times 10^{16}$ eV a ratio of the number of showers with anomalous small number of muons of γ-quanta to the number of normal showers is less than 2×10^{-4} (Solov'eva, 1965).

Analyzing the Yakutsk EAS array data we have found the presence of showers without the muon component, we call them anomalous showers. Unfortunately, we haven't data of the showers without muons formed by ultrahigh energy γ-quanta. Not having a clear idea about the origin of these showers we decided to consider their distribution over the celestial sphere.

Here we have excluded from the previous analysis 11 showers (Mikhailov and Nikiforova, 2000) because of the inaccuracy in interpretation of muon data. Before a middle of 1986 the data were registered on a paper punched tape, then they were transferred into a computer. As to above-mentioned showers, the primary records of muons on a punched tape are absent, although a few minutes before and after these 11 showers there are records on the arrival of another showers with a muon component. Now it is difficult to establish the reason for the absence of the record.

From the previous analysis there are 3 showers which were registered after 1987. Note, that in the excluded 11 showers there were 2 clusters (Mikhailov and Nikiforova, 2000) and in the newly-analysed showers 2 clusters were detected.

2 Experimental data

At present, at the Yakutsk EAS array 49 ground-based scintillation detectors of 214 m^2 total area and 5 underground muon detectors of $100m^2$ total area with the registration threshold $E > 1 \times \sec\theta$, GeV (θ is a shower arrival zenith angle) are operated. In this work the showers registered for 1974-1998 are analyzed. We have considered 665 showers with E $> 0.8 \times 10^{19}$ eV and $\theta < 60^\circ$ and axes which are inside the perimeter of the array. Among them 24 showers have energies above 4×10^{19}eV. The accuracy of determination of the primary particle energy is $\sim$ 30% and for the arrival angle it is $\sim 3^\circ$.

3 Data analysis and discussion

3.1 Showers without muons

All observed registration time is divided into separate time periods of 6 hours. Time periods, when muon detectors not operated, have been excluded from the consideration. When the muon detectors were in operation, we selected the showers with zero muon component.

The probability that muon detectors will not operate is

$$P = \prod(P_{1i} + P_{2i}), \tag{2}$$

where $P_{1i} = \exp(-\rho_i S_i \times \cos\theta)$ is the probability that no one particle would fall into the i - detector, ρ_i is the expected

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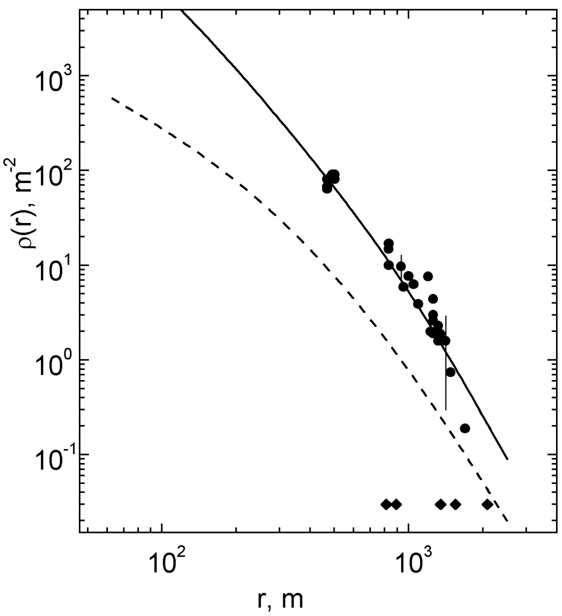

Fig. 1. The observed and expected densities $\rho(r)$ of the electron-photon component (circles) and muon component (rhombuses and dashed line) depending on the distance r of a shower axis. The muon component in all 5 detectors is zero.

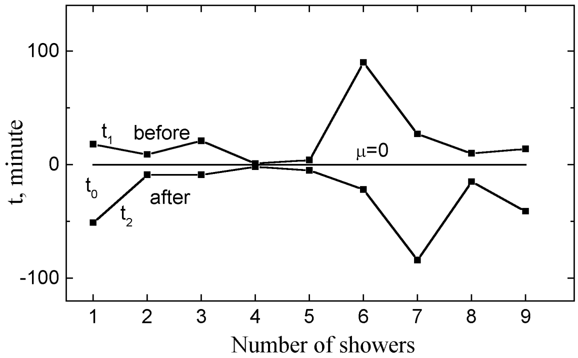

Fig. 2. Times of the shower arrival in min with muons before (t_1) and after (t_2) the time of shower arrival without muons (t_0).

particle density, S_i is the area of the i - detector, θ is a zenith angle; $P_{2i} = 0.5N\exp(-N)$ is the probability that one particle will fall to the detector and it will not operate, 0.5 is the probability that the detector will not operate from one particle, N is the expected number of particles. If the probability is $P > 10^{-3}$, then the given shower is excluded from the consideration. After such a procedure 9 showers were selected from 665 showers. At the energy above $4{\times}10^{19}$ eV there is no any shower without muons. A portion of anomalous showers relative to the number of showers with the normal muon composition is $\sim 2\%$.

Fig.1 shows the observed densities of electron-photon (circles) and muon (rhombuses) components depending on the distance of a shower axis (shower of 8.12.1994 , $E = 2.0 \times 10^{19}$ eV, $\theta = 18°.1$). The shower muon component in all five muon detectors is equal to zero. The probability that no one particle will fall into muon detectors is equal to $P \sim 10^{-20}$. The lateral distribution function of the electron-photon component is shown by a solid line and of the expected muon component - by a dashed line (Glushkov et al, 1995).

Fig.2 presents times of the muon showers (in minute) arriving before and after the shower without muons. For example, $t_1 = 8$ min before the arriving of the above considered shower of 8.12.1994,(Fig.1) the shower with energy $2{\times}10^{17}$ eV arrived and one detector has registered muons, $t_2 = 9$ min after the considered shower the shower with the energy $1.4{\times}10^{18}$ eV arrived and 3 detectors have registered the muon (in Fig.2 these showers are marked as the number 2).

As seen from Figures 1,2 in the ultrahigh energy region there are showers without muons.

3.2 Showers with poor muons

We have revealed showers whose muon density is lower than the expected one in usual showers. Fig.3 shows the shower of 24.4.1991 in which, the number of muons at a distance of 851 m of a core is $n_1 = 4.7$ muons/detector, that is lower by a factor of 3.2σ than the expected number $n_2 = 28.1$ muons/detector, where

$$\sigma = (n_1 - n_2)/\, \delta n_2, \tag{3}$$

and $\delta n_2 = n_2\sqrt{0.025 + 1.2/n_2}$)=7.3 is found taking into account of errors of measurements. For the whole observation period 6 such showers were registered, their contribution to the total number of showers was $\sim 1\%$.

3.3 Arrival directions of showers

Fig.4 presents the distribution of anomalous showers (circles) in the equatorial coordinate system (δ - declination, RA - right ascension). Note that the Yakutsk EAS array detects only showers of the northern part of celestial sphere with $\delta > 2°$. In paper (Mikhailov, 1999) we shown that the arrival directions of showers correlated with pulsars. From 9 showers without the muon component only 2 showers are inside of 3° from pulsars (catalogue of Line and Graham-Smith, 1990). The probability of chance for such a location is P=0.4.

In the shower distribution two clusters, a doublet and a triplet, are observed (see Fig.3, Table). In the doublet the distance between showers is 1.8° , in the triplet the distance from the central shower with coordinates $\delta = 74.0°$ and $RA = 92.5°$ to two another showers is 7°. The nearest pulsar PSR 0450+55 is at a distance 8° from the doublet, the pulsar PSR 0809+74 is at a distance 2.5° from the central shower of triplet.

The probability of chance to form the doublet and the triplet from 9 showers with the above-mentioned distances between

Table 1. Details for showers without muon component forming doublet and triplet.

The number of clusters	Date	Energy, EeV	δ, degree	RA, degree	b, degree	l, degree
1	25.04.1996	8.7	60.2	81.7	14.1	151.7
1	26.03.1998	8.0	57.6	85.4	14.5	155.1
2	27.01.1992	12.6	70.0	148.3	40.6	141.3
2	18.03.1994	46.7	74.0	92.5	23.6	140.3
2	8.12.1994	20.0	76.5	123.1	31.4	137.8

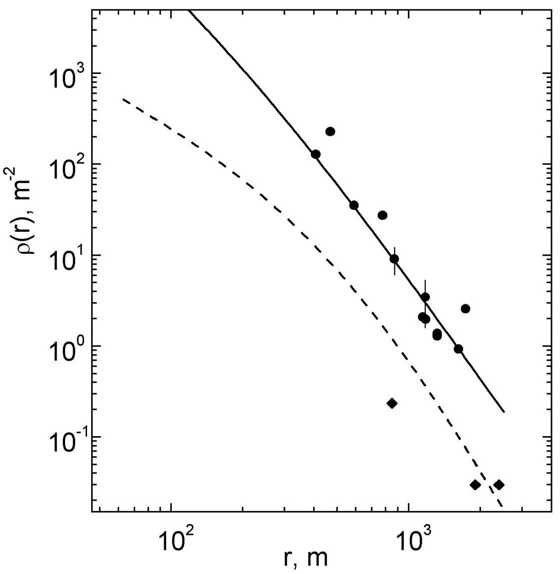

Fig. 3. The observed and expected densities $\rho(r)$ of the electron-photon component (circles) and muon component (rhombuses and dashed line) depending on the distance r of the shower core. The muon component in all 5 detectors is zero.

showers is $7{\times}10^{-4}$. The probability of chance has been calculated by the relative number of doublets and triplets in the isotropic particle distribution. The isotropic particle distribution has been obtained by a simulation of 9 events taking into account a zenith-angular distribution of showers $dn \sim cos(\theta)sin(\theta)d\theta$ in the horizontal coordinate system. Then the distribution obtained on the assumption of a random time of the event arrival was transferred into the second equatorial coordinate system. The number of simulations is equal to 10^6.

From 6 showers (Fig.4, open circles) with poor muons, 2 showers are at a distance of 4° from pulsars, the probability of chance is P=0.5.

Note, that both clusters are located from the pulsars within the radius $R < 9°$, i.e. 3σ (σ is root-mean-square error). It should be noted that distributions of showers without and poor muon components don't correlate with the galactic plane (only 3 showers are located near the galactic plane, Fig.4.)

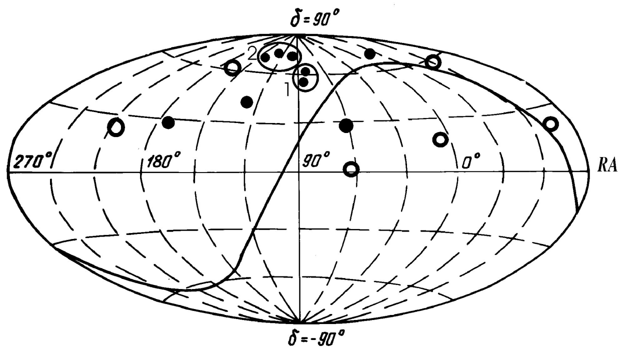

Fig. 4. Distribution of 9 showers without muons (circles) and 6 showers with poor muons (open circles) in equatorial coordinates δ (declination) and RA (right ascension). The doublet 1 and triplet 2 are marked by large circles.

4 Conclusion

In the ultrahigh energy region the showers without and with poor muons have been found. The nature of these showers is unknown. Their contribution to the total number of showers is $\sim 2\%$ and $\sim 1\%$ respectively. Two clusters without muons in the showers, the doublet and the triplet,have been detected.

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