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On the nature of particles that produces extensive air showers with energy greater than 5 EeV

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To study the nature of particles with energies greater than 5 EeV, the database of the Yakutsk array was analyzed. Showers coming one after the other are highlighted within a time interval of 1-20 hours. Some periodicity was found in the registration of such showers during the daily observation cycle with an average time of T = 8 hours. The characteristics of the selected showers: energy, zenith and azimuthal angles were found to be close in magnitude. Consequently, we can assume the same origin nature of the primary particles that initiate such showers. Existing discrepancy in the arrival time of showers at the Earth's level can be attributed to the participation in various processes in outer space: the interaction of particles with different charges with galactic magnetic field, acceleration of particles due to the frictional mechanisms followed by re-emission with higher energy. And time delay at the shock front. If this hypothesis is correct, then the analysis of such air shower events will make it possible to obtain information on the processes of interaction of shock waves with the matter of the Universe.

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1. Introduction

The study of cosmic rays of limiting energies is important for studying the properties of the Universe and, in particular, such a branch of natural science as astrophysics and gamma astronomy [1–3].

The nature of the formation of primary cosmic rays with energies above 10^{18} eV in the Universe is not fully known [4, 5]. According to the models [6–8], it is assumed that in cosmological space, along with the nuclei of various chemical elements, primary photons of high and ultrahigh energies and astrophysical neutrinos. The expected flux of ultrahigh-energy cosmic rays near the Earth will depend on the index of the degree of evolution and the spatial distribution of astrophysical sources [9–11].

Experimentally established irregularities in the cosmic ray spectrum, for example, the first break at an energy of $3 \cdot 10^{15}$ eV [12], the second break at $\sim 2 \cdot 10^{17}$ eV, "deep" and "bump" at $\sim 10^{19}$ eV [13–16], as well as the cutoff of the spectrum at $\sim 5 \cdot 10^{19}$ eV [8, 17], indicate a complex picture of the processes of generation and acceleration of primary particles and as a consequence of their influence on the formation of the cosmic ray spectrum near the Earth. This is primarily due to the distribution of sources in outer space, processes occurring in the sources themselves, the interaction of cosmic rays with matter and magnetic fields in the Universe, their drift in space and interaction with shock waves. This can lead to an increase in the energy of particles, separation in the magnetic field of the shock wave and their subsequent re-emission, both in a direction close to the initial motion, and somewhat different from the latter. Since the flux of cosmic rays consists of charged and neutral particles, we can expect a variety in the mechanisms of interaction and propagation of cosmic rays in cosmological space. The study of cosmic rays with the help of large EAS arrays allows us to get closer to understanding the nature of the origin of cosmic rays and their role in the study of processes occurring on the scale of the Universe.

2. Yakutsk array

The Yakutsk array is medium in size, between compact arrays with an area of s ≥ 1 km^2 and huge arrays with s ≤ 1000 km^2 [18]. The energy range is $10^{15} - 10^{20}$ eV, which allows it to study both galactic and extragalactic cosmic rays. The structure and location of the detectors of the array is shown in Fig.1.

The array consists of 120 main scintillation detectors with a threshold of 10 MeV with receiving area of 2 m^2 each and 72 channels for registering the integral and differential flux of Cherenkov light from EAS [19–22]. Three muon detectors of 20 m^2 each with a threshold of 1 GeV, located at a distance of 300, 500 m and 800 m from the array center. One muon point of 190 m^2 with a threshold of 0.5 GeV, located in the center of the array. Each of the stations has two scintillation detectors and one Cherenkov detector with a receiving area of the photocathode of 176 cm^2 or 530 cm^2.

Observation stations are located on an area of ~13 km^2 with a distance of 500 m from each other. In the central part of the array there is a network of standard observation stations with a distance of 25 m, 50 m, 100 m and 250 m, which have one scintillation and Cherenkov detectors.

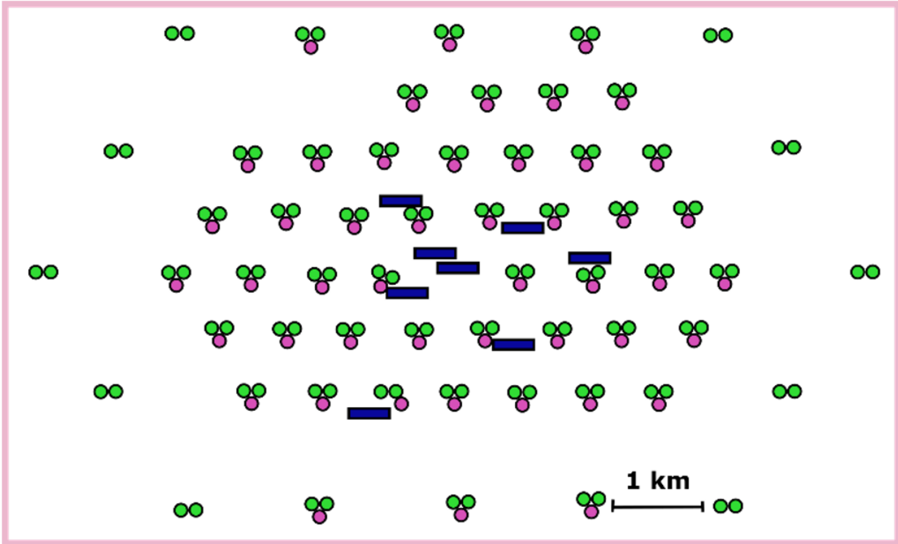

Figure 1: Layout of observation stations at the Yakutsk EAS array. Double dots show stations on the setup, each station has two scintillation detectors, triple dots show stations with Cherenkov detectors, rectangles show muon detectors.

These stations, together with other observation stations, form the basis of a compact array aimed at studying air showers with energy above 10^{15} eV (Fig. 1) [20].

3. Experimental data

In this work, we used data from 1995 to 2014, 1047 showers with an energy of $5 \cdot 10^{18}$ eV. The sample of showers was formed taking into account the following criteria: showers' axes should lie within a circle with a radius of 1000 m from the center of the array; in each shower there should be measurements of muons in the range of distances from 300 to 800 m; The accuracy of determining the axis in showers was $\sigma(X_0)$ — (10-20) m along the (X_0) axis, and (15-25) m along the (Y_0) axis.

The accuracy of determining the density of charged particles and muons at a distance of 600 m was less than or equal to 15%. When these conditions were met, the influence of methodological inaccuracies on the quality of the sample and the determination of the characteristics of showers was minimized. Thus, a sample of "pure" showers was created, excluding events with a "bad" history of registration and mathematical processing.

In this work, we analyzed the database of the Yakutsk array for the detection of paired EAS events that come one after another on a 24-hour time scale. It turned out that such paired EAS events take place in observations, and the arrival times of showers can vary from several hours to 10 hours or more, and the characteristics of showers can be close or slightly different. Table 1 shows the general statistics of showers with $E_0 \geq 5$ EeV and the number of shower pairs selected by observation years.

According to statistics, almost 10% of showers are registered as double events, with the time between events less than 24 hours. Fig. 2 shows the distribution of the time difference between the

Table 1: The total number of showers with $E_0 \geq 5 \cdot 10^{18}$ eV (N), the number of pairs of showers with the time between events less than 24 hours (n), and fraction of pairs in total number of showers (frac.) year by year.

Year	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
N	7	48	49	44	44	53	52	61	55	66	60
n	1	9	5	8	7	6	6	8	7	8	8
frac.	-	0.18	0.10	0.18	0.16	0.11	0.12	0.13	0.13	0.12	0.13

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	Total
N	52	60	52	61	57	52	71	49	54	1047
n	4	7	4	6	3	3	6	5	5	116
frac.	0.08	0.12	0.08	0.10	0.05	0.06	0.08	0.10	0.09	0.11

arrival of the first and second showers Δt. On average, the time difference between the arrival of such showers is 8 hours.

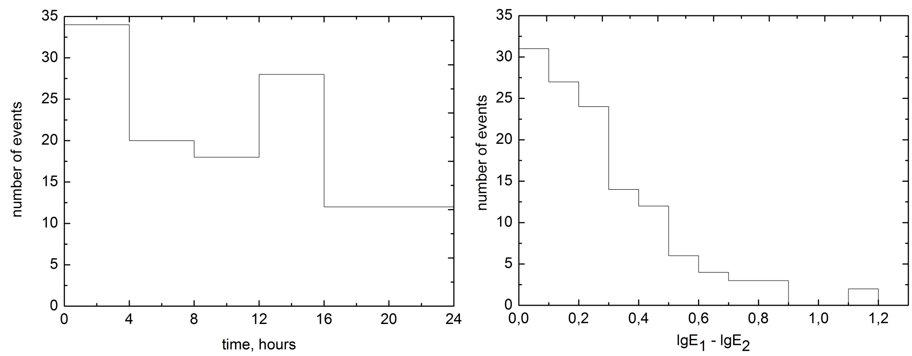

Figure 2: a) Distribution of the time difference of arrival of paired EAS events during a 24-hour observation period over the entire area of the Yakutsk array.b) Difference between the energies of pairs of EAS events. Mean values is $< \Delta(\lg E_0) > = 0.25 \pm 0.02$.

Fig. 2 shows the statistics of paired EAS events that came one after another within 24 hours of observations. It can be seen that the distribution of the difference in the arrival times of pair showers is not uniform. The distribution has a falling character, i.e. showers that follow each other with a time interval of 16-24 hours are noticeably less than those arriving in a shorter period of time. Moreover, it can be seen that in the intervals Δt = 0-4 and 12-16 hours, the statistics of showers is 2-3 times higher than the average in the sample. From this, it can be concluded that EAS events following each other with a short time interval are possibly formed by particles produced in one source or formed during the interaction of a jet of relativistic particles with a shock wave. It can be assumed that EAS events following each other with a short time interval are not random, but for example, formed in one source.

Fig. 3 shows difference between zenith angles of pairs of EAS.

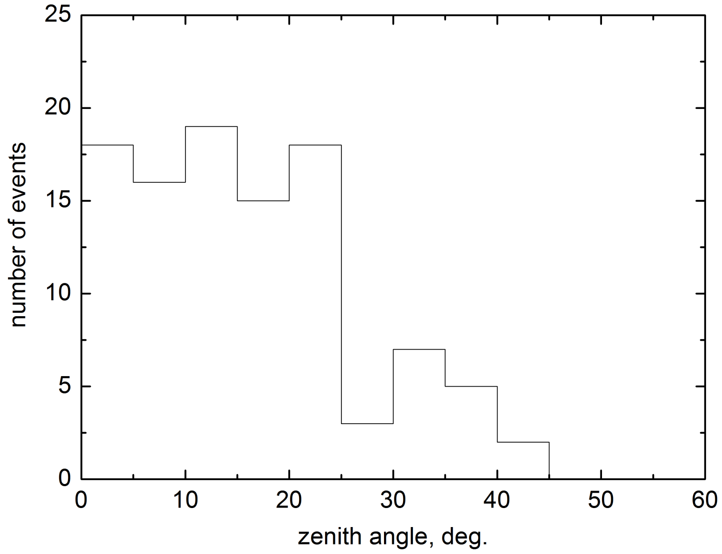

Figure 3: Distribution of the difference between zenith angles of EAS event pairs. Average value $< \Delta\theta > = 15.59 \pm 1.12$.

4. Distribution of double showers on the celestial sphere. Possible sources of cosmic rays of highest energies

Fig. 4a and 4b show the showers that came one after the other. All showers are plotted on the sky map, in equatorial coordinates.

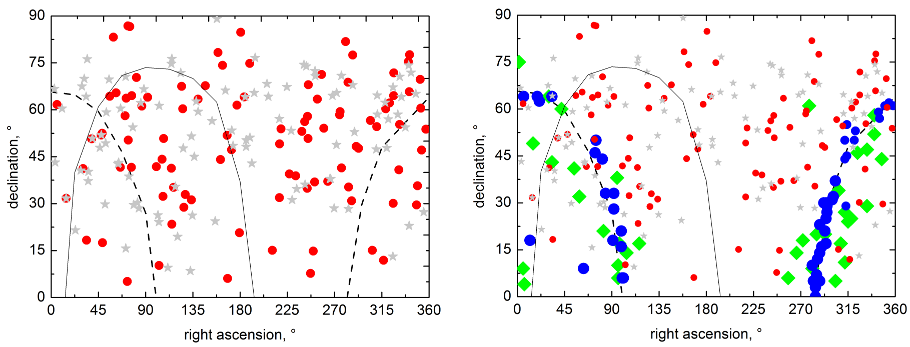

Figure 4: a) Distribution of paired EAS events in equatorial coordinates. Red is the shower that came first, green is the second. The dotted curves on the left and right show the plane of the Galaxy. The dotted curve is the plane of the Supergalaxy. A) shows a less strict selection of EAS events. b) same picture with supernova remnants in the galaxy [23] — blue circles; gamma pulsars — green diamonds [24].

The criterion was T = 24 and $E_0 > 5$ EeV. As can be seen from Fig. 4a, the showers have an isotropic distribution. In Fig. 4a, the red dots show the showers that arrived first, the gray star shows the showers that arrived the second. The solid curve is the plane of the Supergalaxy, the

Table 2: Pairs of air showers with closest characteristics.

Date	Δt [h]	$\Delta \lg E$	$\Delta\Theta[^\circ]$	$\Delta\Phi[^\circ]$	Dec (deg.)	RA. (deg.)	Dec (deg.)	RA. (deg.)
18.04.03	12.13	0.03	11.2	148.1	47.7 °	293.0 °	54.4 °	337.4 °
02.05.03	7.15	0.08	9.9	137.0	55.3 °	332.0 °	64.0 °	337.0 °
31.03.04	1.51	0.01	14.4	16.1	67.7 °	146.8 °	71.8 °	123.0 °
22.01.09	11.11	0.01	7.2	86.7	65.9 °	141.2 °	62.3 °	318.2 °

dashed curve is the plane of the galaxy. Fig. 4b, the same figure with potential CR sources in the galaxy: supernova remnants are indicated by blue circles [23], gamma pulsars are indicated by green diamonds [24].

Table 2 shows pairs of showers with the closest possible characteristics. The time difference between pairs is less than 12 hours, in energy less than 1.08 times.

Fig. 5a shows pairs of showers with close parameters. Fig. 5b shows pairs of showers from table 2.

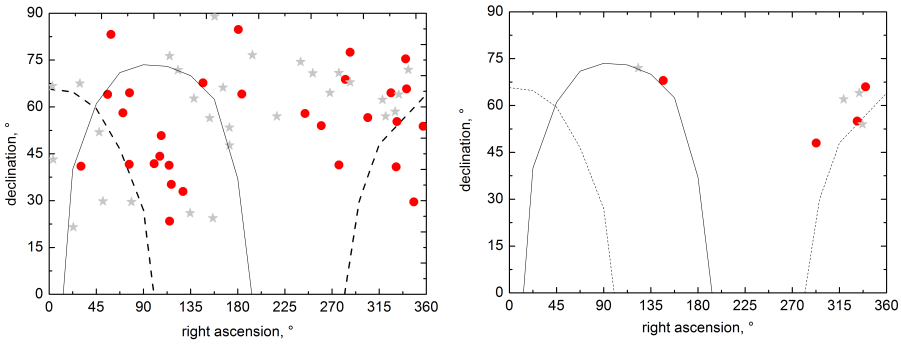

Figure 5: Pairs of showers with close parameters

The general picture of the arrangement of double showers on the sphere, with close parameters (see Fig. 5), nevertheless indicates their compact concentration within the boundaries of the local arm of the Galaxy, which indicates their galactic origin.

Fig. 6 shows the distribution of air showers with $E_0 \geq 5$ EeV on the sky map, coming one after another with an interval of less than 24 hours. The showers had similar characteristics: energy, zenith and azimuth angles. To some extent, they can be considered as paired EAS, although the galactic coordinates in paired showers diverge by 10 degrees or more. Crosses are showers with energies with $E_0 \geq 10$ EeV, registered by the Yakutsk radio array, during the observation periods of 1986–1989 and 2009–2018. Red triangles represent showers with energy $E_0 \sim 100$ EeV, green triangles are showers with very low muon content — candidates for gamma-ray produced air showers [25]. Showers with close parameters, from the Table 2 also plotted here, shown by diamonds and stars. In addition, for comparison, the boundaries of the most active regions with X-ray, radio and optical sources are plotted: the constellation Ursa, Virgo, M82, and Markarian 421. In addition, a hot spot found by TA data [26] is plotted. It can be seen that some of the showers coincide in their coordinates or are close to the boundaries of these regions, which indicates that active regions along with other sources may be sources of cosmic rays with ultra-high energies.

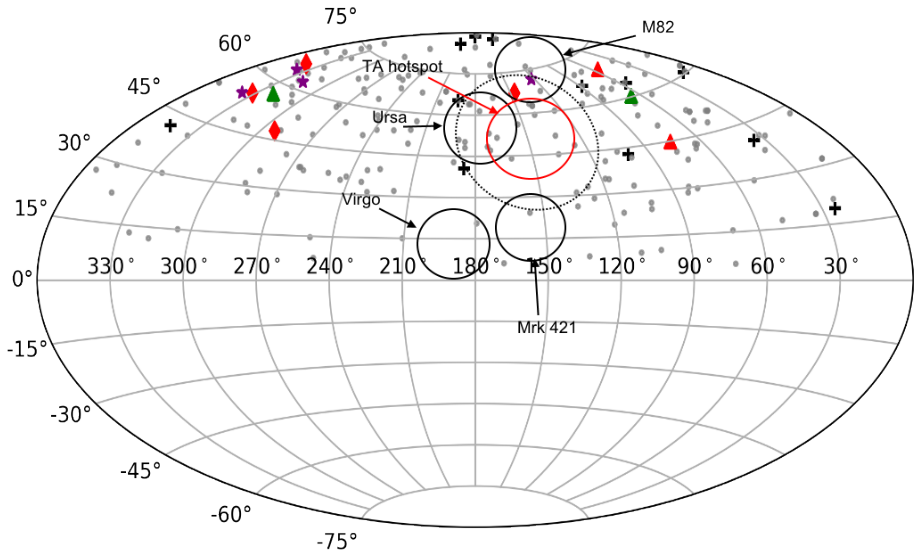

Figure 6: Distribution of the arrival of EAS events with $E_0 \geq 5$ EeV

5. Conclusion

Judging by the analysis of pairs of showers, the nature of the primary particles forming the EAS is diverse. Not all paired events have close declination and right ascension. This could be influenced by uncertainty in locating the shower axis and angles of arrival. In addition, the discrepancy could be explained by the fact that paired showers could have different charges, hence the magnetic field of the shock wave will affect the trajectory of these particles in different ways.

At the same time, there are paired events in which both declination and right ascension are quite close. There are much fewer such events among the selected shower pairs. In Fig. 5, diamonds and stars show showers with the closest parameters, but despite this, their galactic coordinates have a significant discrepancy. Experimental data and available active sources cannot say mainly from which region of the celestial sphere the showers come. Some of the events are concentrated near the galactic plane, and some near the metagalactic plane. The absence of active astronomical objects in this region of the celestial sphere does not mean that they are not there. Perhaps we do not know about these sources yet.

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