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

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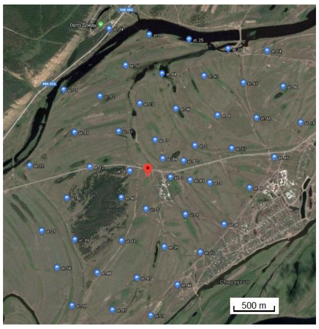
S.P. Knurenko, I.S. Petrov,
Yu.G. Shafer Institute of Cosmophysical Research and Aeronomy SB RAS, Yakutsk, Russia
Contact: igor.petrov@ikfia.ysn.ru.

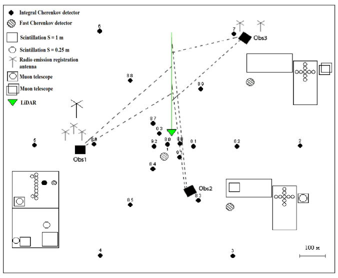
Abstract. To study the nature of particles with energies greater than 5 EeV, the database of the Yakutsk array was analyzed. Showers coming one after the other are highlighted within a time interval of 1-20 hours. Some periodicity was found in the registration of such showers during the daily observation 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.

Yakutsk Array

Location: *61°42' N, 129°24' E;* Height: *110 m*
Area of the array: ~*8 km*^{2}; Energy range: $10^{15} \leq E \leq 10^{20}$ *eV*
58 stations with 120 scintillation detectors $\varepsilon_{thr} \geq 10$ MeV
Spacing: *500 m*
Yakutsk array measures: charged component; muon component; Cherenkov light, radio emission

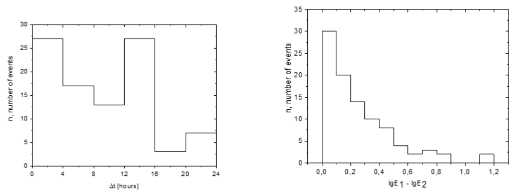


Small Cherenkov array

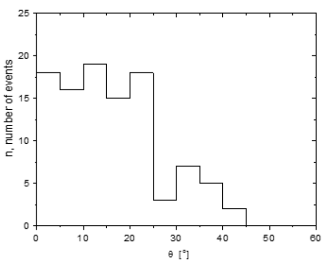


Area of array ~1 km^2. Spacing 50-250 m, 3 tracking Cherenkov detectors at 250, 300 & 500 m from center.

Time distribution of air showers pairs registered at the Yakutsk



We used 2000-2014 data of the Yakutsk array and selected air showers with energy E > 5 EeV and lower zenith angles θ < 60 °, which resulted in 855 events. Second criterion was to select air showers within 24 hours, which decreased our dataset down to 86.
Figure on the left, shows time distribution of air showers. Δt – is the difference between first and second showers, on average its 8 h.
Figure on the right, shows difference between energies of the first and second showers. On average the difference is Δlg(E) = 0.25±0.02.



Zenith angle distribution of air showers in the subset. Average value <Δθ> = 15.59±1.12

Air shower pair events sample

Table 1. Pairs of showers characteristics registered at the Yakutsk array

Data	Time	lgE_0	cosθ	φ	δ	α			ρ_μ/ρ_s	X_{Max}
22.01.14	07:08:49	18,71	0,576	195,9	60,5	352,2	-0,5	113,3	0,047	1048
22.01.14	21:49:08	19,03	0,687	188,5	65,4	193,5	52	122,2	0,410	749

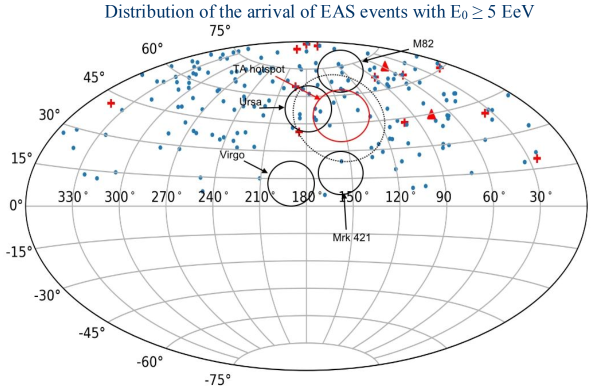
Time difference between two showers is Δt = 14.4 h, zenith and azimuth angles are close. Other characteristics are different – energy of the first shower is smaller, which can be explained by very low X_{max} and low muon fraction. It can be underdeveloped air shower produced by proton, in this case energy would be underestimated. On the other hand it can be produced by γ-ray, which is possible considering low depth of maximum and low muon fraction.

Table 2. Pairs of showers with the most similar properties.

n/n	Date	Δt [h]	ΔlgE	Δθ [°]	Δφ [°]	Latitude (g.c.)	Longitude (g.c.)	Latitude (g.c.)	Longitude (g.c.)
1.	18.04.03	12,13	0,03	11,2	148,1	32,5°	124.2°	37,0°	108,4°
2.	02.05.03	07,15	0,08	9,9	137,0	-0,5°	101.4°	6,3°	107,0°
3.	31.03.04	01,51	0,01	14,4	16,1	41,5°	144.1°	32,4°	143,2°
4.	22.01.09	11,11	0,01	7,2	86,7	6,2°	110.7°	9,5°	100,6°

This table shows air showers with closest characteristics. Δt is 12 and less hours, energy difference is smaller than factor of 1.08 and very close galactic coordinated – less than 5°. Their locations on the sky map are within a circle with radius of 5 °. In this case we can assume that these air showers are originated from the same source of cosmic rays.

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



The figure 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. Crosses are showers with energies with $E_0 \geq 5$ EeV, registered by the Yakutsk radio array, during the observation periods of 1986–1989 and 2009–2018. In addition, 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 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.

Summary

Judging by the analysis of paired showers, the nature of the primary particles producing air showers is diverse. Not all paired events have close declination and right ascension. Perhaps some part of the events diverged more due accuracy of the zenith angle determination. On the other hand, the discrepancy can be influenced by the fact that paired particles can have different charges and, 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. On the table 2 showers with closes characteristics are shown. However, even for those showers, it is clear that the discrepancy between the galactic coordinates of showers is significant. Unfortunately, using experimental data and known active sources we can't explicitly tell from which region of the celestial sphere those showers come. Some of the showers are concentrated near the galactic plane, and some near 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 anything about these sources yet.

References:
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