Search for Sources of Ultrahigh Energy Cosmic Rays

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The arrival directions of ultrahigh energy extensive air showers (EAS) by Yakutsk, AGASA and P. Auger data are considered. It is found that the arrival directions of EAS in the Yakutsk and AGASA data are correlated with pulsars from the side Input, and in the P. Auger data are correlated with pulsars from the Output of the Local Arm of Orion. It is shown that the majority of these pulsars have a short rotation period around their axes, than expected by the pulsar catalogue.

1. INTRODUCTION

First we analyzed extensive air showers (EAS) from the data of the Yakutsk EAS array. Showers with energy \( E > 5 \times 10^{18} \) eV, with zenith angles < 60° and axes lying inside the perimeter of the array are considered. The accuracy of defining the solid angles of arrival directions is 5°-7°, and for energy - ∼ 30%.

Earlier we have found showers with a deficit in the muon content [1]. Theoretical calculations [2] show that the muon content of showers reflects the mass composition of the particles which formed them. Probably, EAS with the usual number of muons are formed by charged particles, and EAS with a deficit by neutral particles.

2. EXPERIMENTAL DATA

Among EAS with a deficit in the number of muons we found 21 EAS without any muon component (the threshold for triggering the muon detectors is > 1 GeV). If the probability of registering these EAS was > 10^-3 the given EAS was excluded from consideration. Each registered shower without a muon component was carefully checked - whether the measured parameters of the EAS are correct. We also found 5 EAS with poor muon number - the muon density at distances > 100 m from the axis was less than expected by more than 3σ.

The celestial co-ordinate distribution of these 26 EAS is shown in Fig.1. The distribution of EAS with a deficit of muons is not isotropic, but some excess in the observed number of EAS is observed from the galactic plane: \( n(|b| < 30°)/n(|b| > 30°) = 1.9 ± 0.7 \). In the case of isotropy this ratio would equal 1.2 according to reference [3].

Among these EAS we found 5 doublets of which 4 are located in one region of the celestial sphere: \( \delta = 20° - 75° \) and \( 60° < RA < 80° \). The fifth doublet has two EAS associated with it, one without muons and the other - muon poor, and is located near the Input of the Local Arm of the Orion Galaxy.

We are interested in this maximum of doublets and consider the distribution of EAS with the usual number of muons as a function of right ascension, RA. We divided the observed energy region \( E > 10^{18} \) eV into 4 intervals:

1) \( 10^{18} - 5 \times 10^{18} \) eV,
2) \( 5 \times 10^{18} - 10^{19} \) eV,
3) \( 10^{19} - 4 \times 10^{19} \) eV,
4) \( > 4 \times 10^{19} \) eV

and the distribution of EAS in right ascension was analyzed by the harmonic functions of Fourier (Fig.2).

Note, that the phase of the 1st harmonic RA ∼ 300° at \( E ∼ 10^{18} \) eV from the Local Arm of the Galaxy varies gradually with energy to RA ∼ 90° at \( E ∼ 4 \times 10^{19} \) eV where 4 doublets are located.

Further we also considered the distribution of EAS in right ascension. We divided the energy region into 3 intervals:

1) \( 5 \times 10^{18} - 10^{19} \) eV,
2) \( 10^{19} - 4 \times 10^{19} \) eV,
Figure 2: Amplitudes $A_1$ and phase’s $RA_1$ 1st harmonic Fourier are shown in energy intervals.

Figure 3: Distribution of particles in energy intervals: a) $E = 5 \times 10^{18} - 10^{19}$ eV; b) $10^{19} - 4 \times 10^{19}$ eV; c) $E > 4 \times 10^{19}$ eV.

3) $> 4 \times 10^{19}$ eV.

The distribution of particles is shown in Fig.3. We observe a maxima of the particle distribution for the 2 first energy intervals at $60^\circ < RA < 90^\circ$. Most likely we observe neutral and charged particles from this region of the celestial sphere.

From the 26 EAS with a deficit of muons only 17 EAS correlate with pulsars within an angular distance of $6^\circ$ (we choose $6^\circ$ because at $E \sim 10^{19}$ eV and at this angular distance from pulsars the correlation between the arrival direction of EAS with the usual number of muons and pulsars was maximum). The arrival directions of these 17 EAS are marked by triangles. The distribution of these EAS which correlate with pulsars is mainly isotropic, but the majority of them are observed near the galactic plane.

Further we considered the arrival directions of EAS with energy $E > 4 \times 10^{19}$ eV - are they correlated with pulsars? Thus, we selected pulsars which are situated at angular distances $< 6^\circ$ from the arrival directions of EAS. From the Yakutsk data we found 19 such EAS from 34 (these EAS are noted by triangles in Fig.4), from the AGASA array - 21 EAS from 57 (Fig.5), and from the P. Auger array - 10 EAS from 27 (Fig.6). The arrival directions of these EAS, which are correlated with pulsars, are situated near...
Figure 6: P. Auger: distribution of particles with $E > 4 \times 10^{19}$ eV. ▲, ●- EAS which are correlated, uncorrelated with pulsars according to the pulsar catalogue [5].

Figure 7: The ratio of the number of pulsars with period $P_0 - n(P_0 < P)/(n(P_0 > P)$: 1 - pulsars, which are correlated with muon poor EAS of Yakutsk; 2 - pulsars, correlated with EAS of Yakutsk; 3 - pulsars, correlated with EAS of AGASA; 4 - pulsars, correlated with EAS of P. Auger; 5 - pulsars according to the catalogue [5].

the galactic plane and at Input (Yakutsk and AGASA) and at Output (P. Auger) of the Local Arm of the Orion Galaxy. Note, earlier we found an anisotropy in the arrival directions of particles with energy $E > 4 \times 10^{19}$ eV from the side Input and Output of the Local Arm from the data of these arrays [5]. It is not possible to explain the correlation with pulsars and the anisotropy arrival directions of EAS by an extragalactic origin of particles.

We considered the rotation periods of pulsars which are correlated with EAS. The ratio of the number of pulsars with periods $P_0 < P$ to the number of pulsars which have periods $P_0 > P$ is shown in Fig.7 (for the Yakutsk array we considered EAS with a deficit and with the usual number of muons). As seen in Fig.7 the majority of pulsars have shorter periods, $P_0$, than expected according to the pulsar catalogue. Some authors have shown that short period pulsars can accelerate heavy nuclei up to $10^{20}$ eV [10, 11].

3. CONCLUSION

The analysis of EAS from the Yakutsk data having a deficit in muon content shows that a third of them form doublets which are located mainly at right ascension $60^\circ < RA < 90^\circ$. At these coordinates a maximum distribution of normal EAS at energy $E \sim 10^{19}$ eV is observed in the Yakutsk data.

It is found that particles with energy $E > 4 \times 10^{19}$ eV in the Yakutsk data, and AGASA and P. Auger data are correlated with pulsars which are situated near the Input and Output of the Local Arm of the Orion Galaxy. The majority of these pulsars have a short rotation period around their axes. The anisotropy and correlation of EAS with pulsars from the side Local Arm of the Orion Galaxy is difficult to explain by an extragalactic origin of cosmic rays. Most likely cosmic rays are of galactic origin and their sources are pulsars.

This paper has been supported by RFBR (project N 08-02-0497).

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