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On the galactic origin of ultrahigh energy cosmic rays

A. A. Mikhailov

Institute of Cosmophysical Research and Aeronomy, 31 Lenin Ave., 677891 Yakutsk, Russia

Abstract. At the energy of $5\times10^{18}-2\times10^{19}$ eV the excess flux of particles by 4.2σ more has been detected than it is expected in the case of the isotropy from the Galaxy plane. The particle fluxes inside the definite radius around pulsars exceeding by $>3\sigma$ expected ones in the case of the isotropy are observed . The list of these pulsars is given. The problem of chemical composition of ultrahigh energy cosmic rays is discussed.

1 Introduction

We have considered the arrival directions of extensive air showers (EAS') registered at the Yakutsk EAS array for 1974 to 1995. The data present the arrival directions of showers with energies $>10^{18}eV$. But the main analysis has been carried out in the energy region $(0.8-4)\times10^{19}eV$. In this energy region 576 showers with the zenith angles $\theta<60°$ and axes located inside the perimeter of array have been analyzed. The accuracy of determination of the primary particle energy generating these showers is $\sim 30\%$, and for the arrival angle it is $\leq 3°$. The arrival directions of showers with E$>4\times10^{19}eV$ have not been considered. We believe that in this energy region cosmic rays are of the extragalactic origin (Efimov et al., 1980).

2 Particle flux from the galactic plane

2.1 Detection of a particle flux

Fig.1 shows the distribution of showers $(0.8-4)\times10^{19}eV$ in galactic latitude b every $3°$. The showers are shown by histograms, the expected numbers of events in the case of the isotropy is the dashed line. The expected numbers of events have been determined by a simulation of 10^6 numbers of random events using the Monte-Carlo method. The events are simulated in the horizontal coordinate system taking into account the zenith-azimuth distribution of showers $dn\sim\cos\theta\sin\theta d\theta$. Then on the assumption of the random uniform arrival time of particles the obtained distribution of the events has been transferred into the galactic coordinate system and normalized to the observed number of showers.

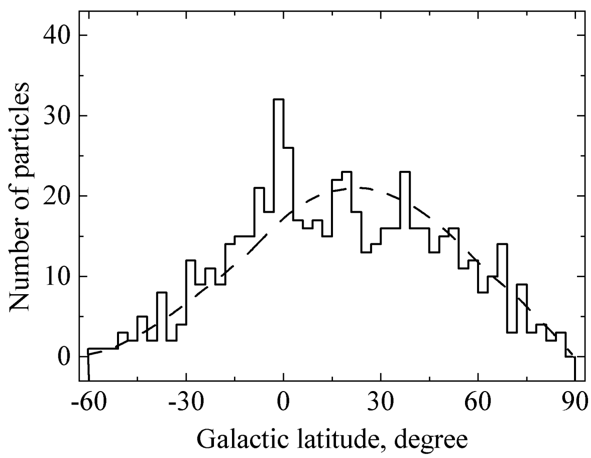


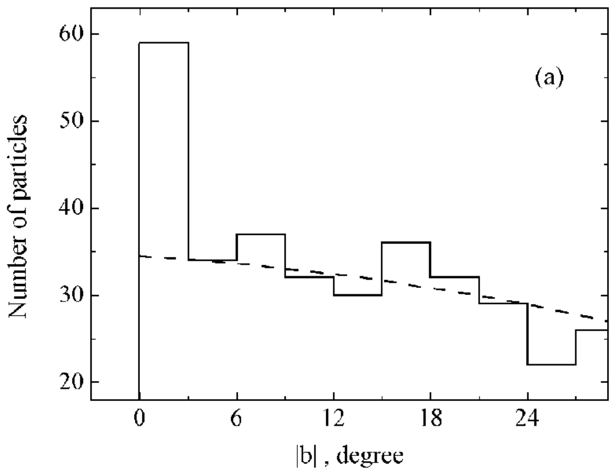
Fig. 1. The distribution of showers in latitude (histograms), dashed line is the expected number of showers in the case of the isotropy.

As seen from Fig.1, at latitudes $b\sim0°$ the excess of the number of showers in comparison with the expected ones is observed. We have joined showers at $3°$ lying at the equal distance from the galactic plane (Fig.2,(a)). In the latitude interval $|b|<3°$ the excess of the number of showers is 4.2σ, where

$$\sigma=(n_{obs}-n_{ran}/\delta n_{ran}, \qquad (1)$$

the observed and expected numbers of showers are equal to $n_{obs}=59$, $n_{ran}=34.4$, respectively, σn_{ran} is the uncertainty of the expected events.

Correspondence to: A. A. Mikhailov (mikhailov@ikfia.ysn.ru)



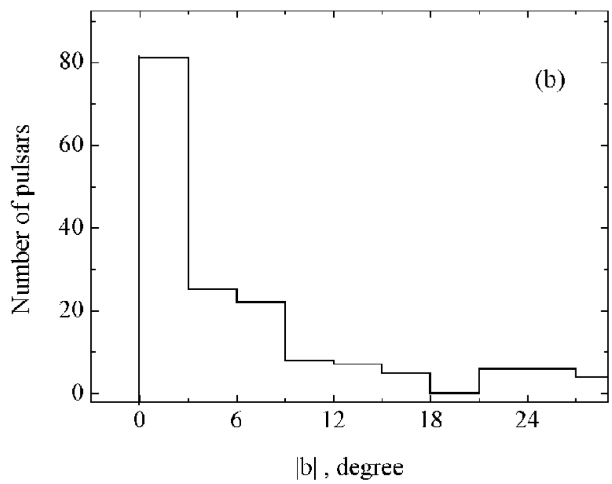


Fig. 2. (a) - The distribution of showers depending on the distance from the galactic plane (histograms), the expected number of showers - the dashed line; (b)- the distribution of pulsars with $\delta > 2°$.

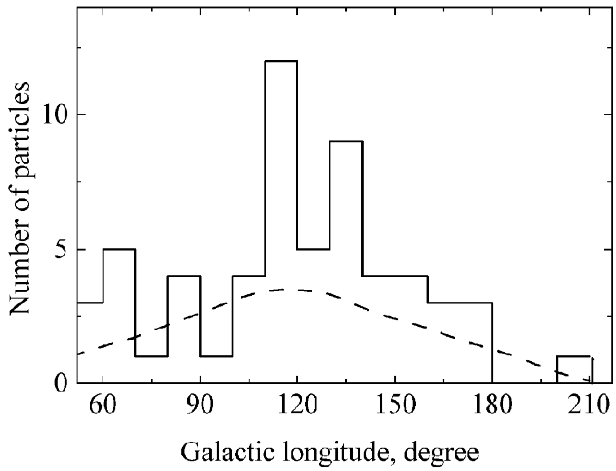


Fig. 3. The distribution of showers with $|b| < 3°$ (histograms)and the expected number of particles (dashed line.

Fig.2,(b) presents the distribution of pulsars depending on their distances of the galactic plane every $3°$ which are visible at the Yakutsk EAS array at the zenith angles $\theta < 60°$. Note, these two distributions of both showers and pulsars in galactic latitude are similar. Probably, this similarity is no chance. In (Mikhailov, 1999) we showed that the arrival directions of cosmic rays correlated with the pulsars.

From the side of the galactic plane a direct particle flux with the energy $(0.8 - 4) \times 10^{19} eV$ has been detected. The excess of the number of showers over the expected one in the case of isotropy is 4.2σ.

2.2 Particle fluxes from the Galaxy plane and pulsars

Fig.3 displays the distribution of showers arriving from the latitude $|b| < 3°$. At longitudes $110° < l < 140°$ two maxima of the shower arrival directions are observed in comparison with the expected events. The excess of the observed number of showers in the first maximum is $4.5\sigma = (12 - 4.5)/\sqrt{4.5}$, in the second one - $3.7\sigma = (9 - 3.7)/\sqrt{3.7}$. If we join the showers at longitudes $110° - 140°$ then the excess of the observed showers will be $4.9\sigma = (26 - 10.4)/\sqrt{10.4}$. Note, that from the side of two nearest pulsars PSR2334+61 and PSR0154+61 inside the radius $r < 6°$ the excess of showers $4.7\sigma = (18-6.3)/\sqrt{6.3}$ and $3.5\sigma = (15-6.3)/\sqrt{6.3}$ is observed, respectively. Characteristics of pulsars are given in Table 1.

Maxima of particle fluxes are most likely formed by these nearest pulsars.

2.3 Transitional region

Fig.4 shows a ratio of the number of showers from the $|b| < 3°$ to the expected ones in the case of isotropy (circles) in depending on their mean energy. As seen from Fig.4 , this ratio increases with the energy up to 2×10^{19} eV, then it has a tendency to decrease. This decrease is apparently associated with the fact that at the energy $> 2.10^{19}$ eV the extragalactic particles begin to give a contribution.

Thus, the energy region of $(2-4) \times 10^{19}$ eV is most likely a transitional region between the galactic and extragalactic particles.

3 Particle fluxes from pulsars

The map of the celestial sphere in equatorial coordinates shows (Fig.5, δ is the declination, α is the right ascension) the distribution of pulsars from which the inside definite radius the excess of particles is observed. These pulsars are located not far than 1 kpc from the Earth. The isotropic distribution of particles is calculated by the simulation of the random events using the above-mentioned method. The number of particles from pulsars is determined inside the distance of $9°$ from them. This angle corresponds to the triple root-mean-square error in the determination of the shower arrival angle. According to the statistics, inside the triple error from the given

Table 1. *Nearest pulsars with the distance $d < 3$ kpc and from the side of which the particle fluxes $> 3\sigma$ (formular 1).*

Pulsar, PSR	σ	b degree	l, degree	distance, kpc	period, sec	age, 10^5 year
0144+59	3.1	-2.7	130.1	1.1	0.19	125.9
0154+61	3.5	0.3	130.6	0.7	2.35	1.99
1919+21	3.4	3.5	55.8	0.3	1.33	158.5
1919+20	3.2	2.6	54.2	2.1	0.76	
1931+24	3.6	2.4	59.2	2.7	0.81	
1935+25	3.5	2.3	60.8	1.8	0.20	19.9
1937+24	3.6	1.4	60.3	2.8	0.64	
1957+20	3.1	-4.6	59.2	0.8	0.001	
2306+55	3.9	-4.2	108.7	1.5	0.47	398.1
2319+60	3.8	-0.6	112.1	2.8	2.25	50.1
2334+61	4.7	0.2	114.3	1.5	0.49	0.4
2351+61	5.1	-0.2	116.2	2.5	0.94	10.0

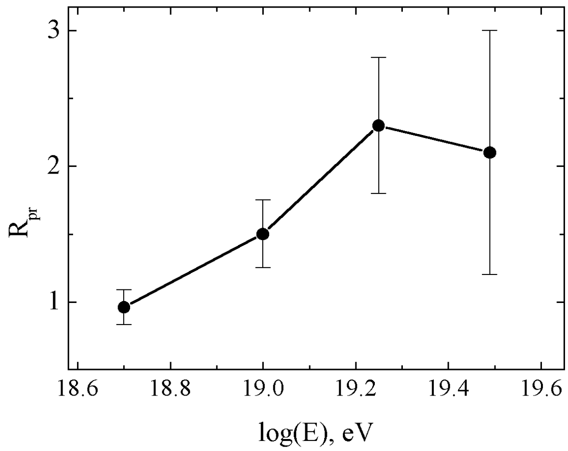


Fig. 4. The ratio of the number of showers at $|b| < 3^\circ$ to the expected one versus the energy of showers.

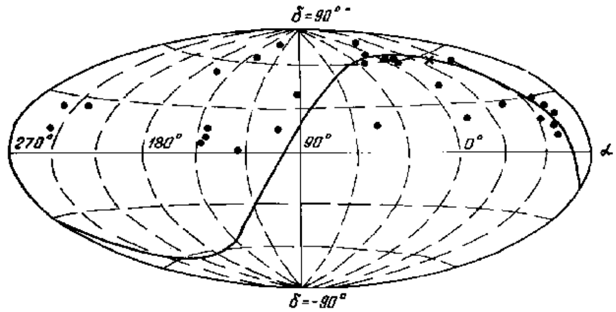


Fig. 5. The distribution of the particle flux inside the radius $r < 9^\circ$ from pulsars with distances < 1 kpc. x - $b = 0^\circ$, $l = 90^\circ$. The solid line is the galactic plane.

source, the particle flux must be $\leq 99.8\%$.

The celestial sphere map (Fig.6) shows the distribution of pulsars, from the side of which inside the radii $r = 6^\circ$and 9° the number of particles excess the expected one in the case of the isotropy more than by 3σ. The choice of radius 6° is caused by the fact that the error the arrival angles for small zenith angles is less than the mean error 3°. So, $r = 6^\circ$ corresponds to pulsars, which are visible at small zenith angles θ.

Fig.6 shows only the distribution of pulsars up to the distance 3 kpc because the pulsars further than 3 kpc practically coincide within 3° (the error in the determination angle) with the nearest pulsars. The characteristics of these pulsars are given in Table 1.

As seen from Fig.6, there are two maxima in the distribution of pulsars: 1) from the direction of force lines of the magnetic field or the Local Arm Input; 2) from the side of central region of the Galaxy. These pulsars are situated $< 45^\circ$ of the galactic field direction. Near the Earth the field has $b \sim 0^\circ$; $l \sim 90^\circ$; or $\delta = 48^\circ.1, \alpha = 317^\circ.5$ (Kronberg, 1996).

The absence of statistically significant particle fluxes from pulsars up to 1 kpc (Fig.5), located across lines of the magnetic field testifies that on the path from pulsars the particles deviate at a large angle and lose its initial direction. From here it is possible to conclude that a main part of particles from the pulsars are not protons and neutral particles. In the magnetic field $H = 2 \times 10^{-6}$ G at the distance 1 kpc the particles with $E = 1.3 \times 10^{19}$ eV deviate across lines of the magnetic field at a angle (Mikhailov, 1980)

$$sinb = 150ZHd/E. \tag{2}$$

At the distance 1 kpc protons deviate at the angle $< 4^\circ$, and at > 0.1 kpc iron nuclei deviate at $> 9^\circ$ (at > 0.5 kpc - at $> 90^\circ$). Thus, the existence of statistically significant particle fluxes from the pulsars depending on their relative orientation to the field lines of the galactic magnetic field testifies, that the ultrahigh energy cosmic rays are charged particles, their charge most likely is $Z > 1$.

4 Conclusion

Cosmic rays up to the energy 2.10^{19} eV are probably the galactic ones and their sources are pulsars. The energy region

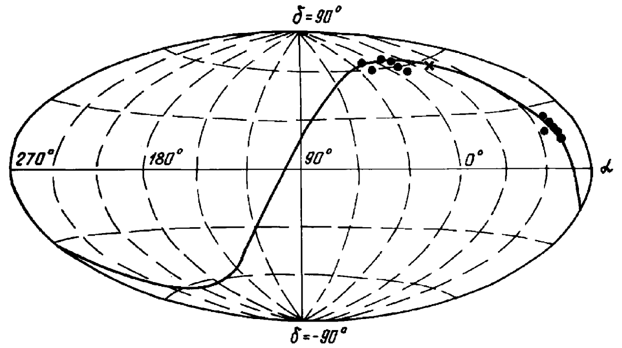


Fig. 6. The distribution of pulsars, from the side of which $> 3\sigma$ excess of the number of particles is observed relative to the expected one in the case isotropy. x - $b = 0°$, $l = 90°$. The solid line is the galactic plane.

$(2-4)\times 10^{19}$ eV is most likely a transitional region between the galactic and extragalactic particles. Cosmic rays at the $\sim 10^{19}$ eV are charged particles, their charge most likely is $Z > 1$.

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