Pulsars Are Possible Sources of Cosmic Rays at E $\geq 4\times10^{19}$ eV

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Abstract

Extensive air showers (EAS) with the energy above $4 \times 10^{19} eV$ that were detected at the Yakutsk array are analyzed. The directions of their arrival are found to correlate with pulsars located in the directions of the Orion Arm of the Galaxy. Data of the AGASA array is discussed.

1. Introduction

In this work, we analyze the distribution of showers with the energy $E > 4\times10^{19}$eV that were detected at the Yakutsk EAS array from 1974 to 2002, when 29 showers, whose arrival axes fell within the array perimeter, were detected.

2. Data of the Yakutsk array

The figure shows the distribution of the showers in the map of the celestial sphere in the second system of equatorial coordinates δ (declination) and RA (right ascension). As is seen, the distribution is almost isotropic, and only 2 clusters are observed at $\delta \sim 27°$, $RA \sim 48°$ and $\delta \sim 60°$, $RA \sim 130°$. The probability of random formation of the 2 clusters inside angle $< 4.5°$ from each other among 29 uniformly distributed showers is $P \sim 0.5$.

Futher, we determined correlation between the arrival directions of showers and pulsars[1]. To this end, we took the following directions: (I) over the entire celestial sphere region visible by the array and (II) along the field lines of the large-scale regular magnetic field in the directions of the Orion Arm within a cone with angle $R < 45°$ (dashed line in figure) from the field-line axis with the galactic coordinates $b = 0°$ and $l = 90°$. This direction was chosen, because the magnetic field minimally deviates particles moving along field lines, and the probability of correlation between shower arrival directions and pulsars increased.

We calculated the angular distances between the arrival direction of each shower and all pulsars and determined the number $n(\theta)$ of showers observed within the angle θ from pulsars. A given shower was considered only once and to the minimum angle θ. The probability P of the randomness of the number $n(\theta)$ of

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showers was calculated by the Monte-Carlo method through drawing 29 events distributed isotropically over the celestial sphere (for details, see [2]).

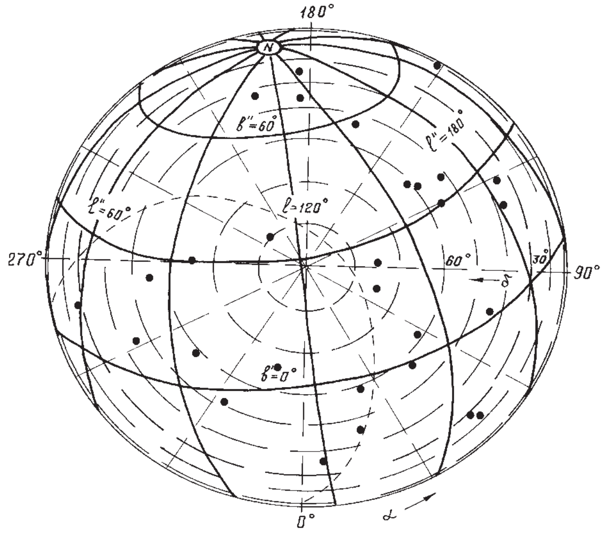

Fig. 1. Distribution of 29 showers with $E > 4 \times 10^{19}$eV in the map of the celestial sphere; δ and RA are the declination and right ascension, the dashed line is the conditional boundary of the Orion Arm, $R < 45°$.

Analysis shows that correlation between the particle arrival directions with pulsars is observed only in the direction of the Orion Arm of the Galaxy. Among 11 showers arrived from the direction of the Orion Arm (Fig.1), 10 showers (Table 1,Yak.) fall within the angle $\theta < 6°$ from pulsars. The Table 1 presents the shower arrival date (year,month,day), its coordinate, pulsars. The probability of random observation of 10 showers within $\theta < 6°$ from pulsars is P=0.05. Among the remaining 18 showers beyond the Orion Arm $R > 45°$, only 6 are within $\theta < 6°$ from pulsars. The probability of the randomness event is $P \sim 0.8$.

The shower with the maximum observed energy $E = 3.2 \times 10^{20}$eV was detected at the Fly's Eye array (USA) and was interpreted in [3] as being formed by the gold nucleus. At this array, in contrast to the Yakutsk array and AGASA array, the development of a shower in the atmosphere is directly measured by detecting ionization radiation of air atoms excited by the particles of the shower.

For the benefit of gold nucleus behaviour of the characteristics EAS at $E > 4 \times 10^{19}$ eV on the data of array Yakutsk testify: 1) the number of muon in EAS increase with energy [4], 2) the distribution of EAS on zenith angles differs from distribution of EAS at $E \sim 10^{19}$ eV, in particular, maximum of distribution is displaced from $50° - 60°$ [2] to $20° - 30°$ (here we have no a place for show).

The mean lifetime of gold nuclei in the Galaxy is equal to the mean lifetime of protons with energy $E_p = E_{Au}/z$ (z is the charge of Au). Calculations made in

Table 1. Showers (Yak.=Yakutsk, AG.=AGASA) that arrived from the direction of the Orion Arm and had $E > 4 \times 10^{19}$ eV and pulsars correlating with them, $\theta < 6°$.

n	Date, Yak.	RA,δ,deg	Pulsar, PSR	Date,AG.	RA,δ,deg	Pulsar, PSR
1	880116	8.7+36.3	0045+33	930612	19.0+50.0	0052+51
2	960126	21.3+45.7	0053+47	920124	268.0+47.9	1753+52
3	891019	24.0+57.0	0136+57	841217	277.2+35.3	1811+40
4	911201	235.4+79.8	1322+83	980903	294.0+50.7	1953+50
5	990221	274.2+54.5	1839+56	961022	298.5+18.7	1929+20
6	891215	283.5+29.3	1912+25	961112	324.2+08.1	2127+11
7	851104	297.3+45.2	1953+50	871126	329.2+27.6	2210+29
8	950113	314.8+57.8	2045+56	841212	335.2+38.4	2154+40
9	851026	335.2+51.0	2217+47	990925	340.0+42.6	2217+47
10	830208	342.9+65.8	2224+65	990922	345.7+33.9	2303+30

[5] show that the lifetime of Au nuclei with $E_{Au} = 4 \times 10^{19}$eV is longer than the lifetime of protons with the same energy by a factor of 10 and is equal to $\sim 10^5$yr. This particle lifetime is sufficient to the isotropization of their arrival directions [5,6] and is much less than time $\sim 10^8$yr [7,8] necessary for the formation of the spectrum with cutoff caused by their interaction with the relict radiation.

3. Data of the AGASA array

Inside of a cone with $R < 45°$ angle relative to an axis of magnetic field lines in the Orion Local Arm there are n_1=18 showers among 57 EAS with $E > 4 \times 10^{19}$ eV[9]. 10 (n_2) showers (Table 1, AG.) of their are within 6° from the pulsars. The probability of chance is P=0.6. However, this method of analysis is low-sensitive when the number of showers correlated with the pulsars n_2 is small in comparison with the total number of showers $n_2 < n_1$.

Consider the another analysis method: determine a portion of showers which correlate with pulsars per one pulsar from a side of the Orion Arm, $R < 45°$ and outside this Arm, $R > 45°$ (formula 1). The central part of the Galaxy with longitudes $l < 60°$, where the many group of pulsars is observed, has been excluded from the analysis. The remaining 49 showers are the declinations $\delta > 5°$, therefore we consider pulsars with $\delta > 0°$ - $n = 131$. A ratio of the number of showers $n_1 = 9$ correlated with the pulsars to the total number of showers n_2=17 and pulsars n_3=83 from the direction of the Orion Arm $R < 45°$ to identical parameters outside of the Orion Arm $R > 45°$ $m_1 = 5$, $m_2 = 32$, $m_3 = 48$ is

$$n_1/(n_2 \times n_3) : m_1/(m_2 \times m_3) = \frac{9}{17 \times 83} : \frac{5}{32 \times 48} \sim 2 \tag{1}$$

The number of showers from $R < 45°$ which correlate with pulsars is greater than $R > 45°$ or along magnetic field lines showers correlate with pulsars. Thus, this analysis confirms the results obtained by us. Note that ratio (1) for the Yakutsk array is ~ 4.

4. Conclusion

According to data reported in [10,11,12], the chemical composition of cosmic rays changes gradually to heavier elements with energy; protons prevail (92.5%) for energies $\sim 10^{10}$eV [10], heavy nuclei dominate for $\geq 3 \times 10^{15}$ [10], iron nuclei prevail for $\sim 10^{19}$eV [11], and gold nuclei dominate for $\sim 10^{20}$eV [3]. The change in the spectrum of cosmic rays [10] for $\sim 3 \times 10^{15}$, 6×10^{17}, and 10^{19}eV is apparently caused by a change in the chemical composition of particles.

One can conclude that cosmic rays originate, in all likelihood, from pulsars.

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E=Energy, eV
δ=Declination, degree
RA=Right ascension, degree
R, θ=Angles, degree
n_1, n_2, m_1, m_2=Number of EAS
n_3, m_3=Number of pulsars

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