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Arrival directions and chemical composition of ultrahigh energy cosmic rays

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Abstract. To estimate the chemical composition of ultrahigh energy cosmic rays we apply an approach using the well established magnitude and character of the Galaxy magnetic field and also both theoretical and experimental distributions of showers in galactic latitude. Arrival directions of cosmic rays in the energy region of (0.8-4)$\times 10^{19}$ eV in galactic latitude will be consistent with theoretical calculations, if cosmic rays are mainly heavy nuclei. The north-south asymmetry in the distribution of cosmic rays at $\sim 10^{19} eV$ is found. The deviation from a isotropy is 6.2σ.

1 Introduction

The estimation of the chemical composition of cosmic rays by the maximum depth of shower development using the Yakutsk extensive air shower (EAS) array data (Afanasiev et al., 1966) and model calculations of NN and πN interactions of ultrahigh energy particles show that at the energies E $\sim 10^{18} - 10^{19} eV$ in the primary radiation the protons are prevalent. The analogous estimation of chemical composition was made in (Bird et al., 1993) by Fly's Eye array data, authors of which assumed that at 10^{19} eV the protons were no less than 90%. Authors of (Wolfendale et al., 1999) by using a new model of interactions of particles by shower development maximum concluded that $E < 3 \times 10^{18}$ eV cosmic rays are heavy nuclei, and at E $> 3 \times 10^{18}$ eV the portion of heavy nuclei is $\sim 50\%$.

As seen from (Afanasiev et al., 1996, Wolfendale et al., 1999), there are the contradiction in the estimations of the chemical composition. Note, that the analysis of the Yakutsk array data testifies that at the energy $> 5 \times 10^{18}$ eV the prefential increase of a relative portion of muons in the total charged particle flux is observed (Glushkov et al., 1999). This fact contradicts the conclusion of (Afanasiev et al., 1996).

In the present paper we estimate the chemical primary composition by the number of observed and expected showers in galactic latitude.

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2 Experimental data

In (Efimov et al., 1990) and other papers the authors showed that E $> 4 \times 10^{19}$ eV cosmic rays are most likely extragalactic. We analyze arrival directions of 576 showers with energies (0.8-4)$\times 10^{19} eV$, zenith angles $< 60^\circ$ and axes lying inside of the perimeter of the Yakutsk array for 1974 - 1995. The mean energy of showers is 1.3$\times 10^{19}$ eV.

3 Calculations

We consider the disc magnetic field model suggested in (Rand and Kulkarni, 1989) and constructed on the basis of determination of the Faraday's rotation measure of radio emissions from pulsars. The main component of the magnetic field is the azimuth component of ~ 2 μG magnitude. The radial and z - components are one order of magnitude smaller. Except for the regular components there exists the irregular component of 5 μG magnitude and characteristic size of 100 pc. The sizes of the disc: a radius is 15 kpc, half-height is 0.4 kpc. As in (Berezinsky et al.,1979) we suggest the existence of the magnetic field outside of the Galaxy's disc - in a halo of the Galaxy. This field has both the regular and irregular components. The magnitude of the main azimuth regular component of the magnetic field in the Galaxy's halo is $\sim 1 \times f(z) \mu$G, (where f(z) = exp$\left(\frac{|z|-0.4}{5kpc}\right)$), for the irregular component it is 1.5 μG with a characteristic size of 500 pc and a half-height of the halo of 5 kpc.

We consider two cases for the distribution of cosmic ray sources: 1) sources are uniformly distributed over the Galaxy's disc, 2) sources are pulsars (Mikhailov, 1999 and in other papers we showed that cosmic ray sources most likely are pulsars). The distribution of pulsars in radius r and in height

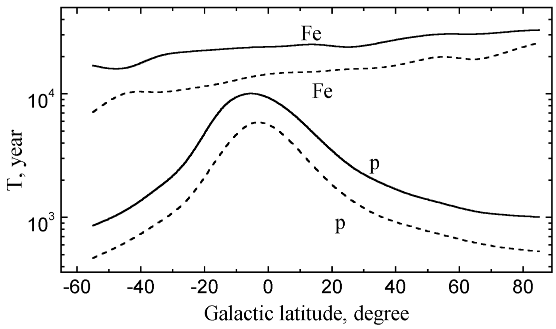

Fig. 1. The path length (intensities) of protons (p) and iron nuclei (Fe) with the energy $1.3 \times 10^{19} eV$. The solid lines - the sources are distributed uniformly over the whole disc, the dashed lines - sources are the pulsars.

z across of the Galaxy's disc is described by a function:

$$f(r, z) = f_1(r) \times f_2(z), \qquad (1)$$

where $f_1(r) = (1-exp(r^2/8)) \times exp(-r^2/100)$, $f_2(z) = 1/0.46 \times exp(-|z|/0.23)$. The function $f_1(r)$ is found by an approximation of the observed distribution of pulsars (Manchester, 1977), the function $f_2(z)$ is taken from (Manchester, 1977).

To determine the expected particle flux we have calculated trajectories of antiparticles from the Earth to their exit beyond the halo. The antiparticle trajectories correspond to the positive charged particle trajectories from the sources to the Earth. The expected particle flux in the given direction is assumed to be proportional to an antiparticle path length and a density of sources in the Galaxy's disc.

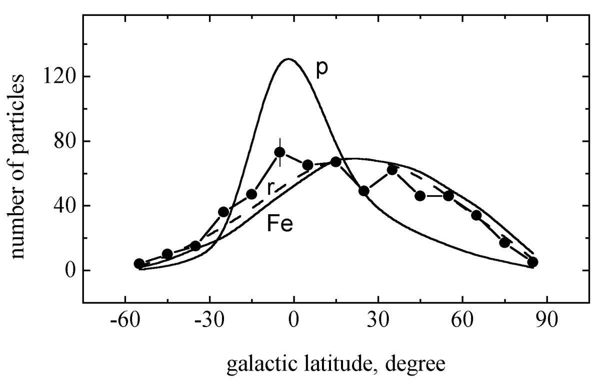

Fig. 2. The observed (circles connected by a line) and expected numbers of EAS events in the case of protons (p) and iron nuclei (Fe) in galactic latitude. The dashed line (r) - the expected numbers of showers in the case of the isotropy.

We consider the antiproton trajectories for energies 5×10^{17} eV and 1.3×10^{19} eV. The energy 1.3×10^{19} eV of antiprotons corresponds to the average energy of considered showers, the energy 5×10^{17} eV corresponds to the generation of showers by iron nuclei. The lifetimes of particles in the Galaxy's disc, or expected intensities of particles depending on their arrival direction in galactic latitude, are shown in Fig.1. In the case of protons, as the harmonic analysis indicates, nearly 100% anisotropy is expected, and in the case of iron nuclei the anisotropy is several percent. Note that the analogous conclusion was obtained for other models of the magnetic field of the disc and halo (Giller et al., 1994). The increase of the halo size to 30 - 100 kpc with magnitude of the field of ~ 1 μG does not change the obtained results (Berezinsky et al., 1991, Lampard et al., 1997).

4 Data analysis

Fig.2 presents the distribution of showers observed in galactic latitude b and the expected numbers of events for protons (p) and iron nuclei (Fe). The expected numbers of events were found by the expected intensity (Fig.1), taking into account of an exposure of the Yakutsk EAS array at the celestial sphere and we normalized their to the observed numbers of showers.

After the normalization the expected number of showers both protons and iron nuclei for two different distributions of sources are coincided. A comparison by the χ - square method of observed and expected distributions of the number of showers originated by protons and iron nuclei in galactic latitude shows that a minimum value of χ - square will be achieved, if a portion of iron nuclei at E $\sim 10^{19}$ eV is $\sim 80\%$.

5 North-south (N-S) asymmetry

In Fig.2 the distribution of the expected number of events in latitude l (dashed line,r, which practically coincides with the curve for Fe) in the case of primary radiation isotropy is shown. The expected numbers of events are determined by a simulation of 10^6 random events using the Monte-Carlo method. The events are simulated in the horizontal coordinate system taking into account of the zenith-azimuth distribution of showers $dn \sim \cos\theta \sin\theta d\theta$. Then on the assumption of the random uniform arrival time the obtained event distribution of the showers has been transferred into the galactic coordinate system and normalized to the observed number of showers.

As seen from Fig.2, in the shower distribution in comparison with the expected ones in the case of isotropy the excess of showers is observed at latitude $b < 0°$ and the deficiency of showers - at $b > 0°$. This difference in the shower distribution from the isotropy we call the N-S asymmetry and consider it in detail.

As it is predicted in the galactic origin model, there exists the N-S asymmetry in the ultrahigh energy particle distribution due to the focusing of particles by the azimuth component of the galactic field (Syrovatsky, 1969). The N-S asymmetry of particles was discussed in papers (Efimov et al.,

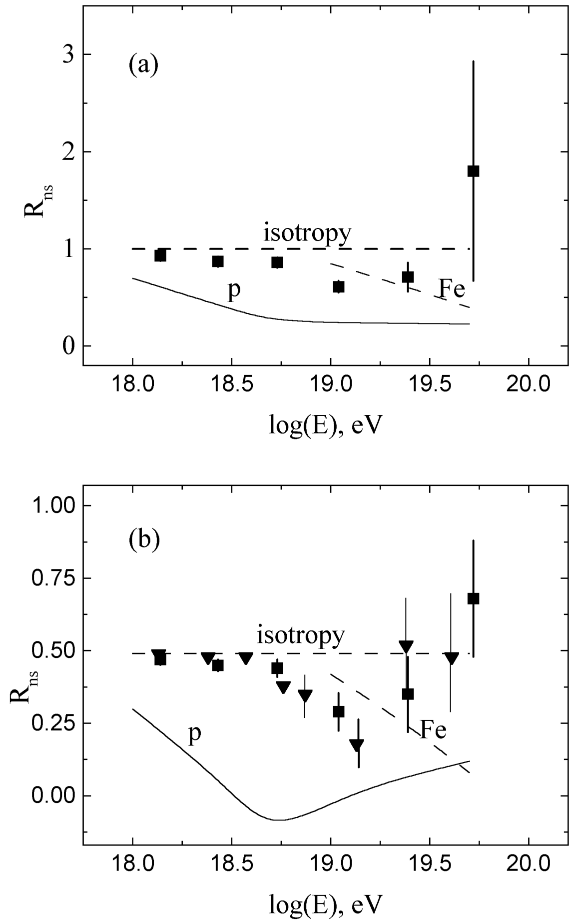

Fig. 3. N-S asymmetry R_{ns} (squares) versus the energy of EAS: (a) - $R_{ns} = n_1S_2/n_2S_1$, (b) - $R_{ns} = (n_1 - n_2)/(n_1 + n_2)$. The curves are the expected R_{ns} for protons p and iron nuclei Fe. Triangles - data by Ivanov, (1998). The horizontal dashed line is expected R_{ns} for the isotropy.

1983, Ivanov, 1998, Wolfendale et al., 1999) and in other ones.

We consider the arrival directions of EAS for the outside Galaxy in longitude $90° < l < 270°$, where the magnetic field is more regulate and the N-S asymmetry will be maximum.

Fig.3,(a) shows the N-S asymmetry obtained by the formula

$$R_{ns} = n_1S_2/n_2S_1, \tag{2}$$

where n_1 is the number of shower at $b > 0°$, and n_2 is the number of shower at $b < 0°$; S_1 and S_2 are the celestial sphere exposure by the array at $b > 0°$ and $b < 0°$, respectively. The exposure of the celestial sphere is found from the cosmic radiation isotropic distribution, as the expected number of particles in the case of isotropy. In the case of the primary radiation isotropy $R_{ns} = 1$. At the energy of showers $> 5 \times 10^{18}$ eV a ratio of the exposures $S_1/S_2 = 2.96$.

As seen from Fig.3,(a) the parameter R_{ns} reaches the maximum deviation from the isotropy at the energy interval $(0.8-1.7) \times 10^{19}eV$, i.e. $R_{ns} = 0.61 \pm 0.06$. The error is

$$\delta R_{ns} = S_2/(S_1 \times \sqrt{n_2}) \times \sqrt{n_1 \times (1 + n_1/n_2)/n_2} \tag{3}$$

or $\delta R_{ns} = 0.06$. The deviation from the isotropy is $D_{ns} = (1 - R_{ns})/\delta R_{ns} = (1 - 0.61)/0.06 = 6.2\sigma$.

Note, if we consider all energy interval $(0.8 - 4) \times 10^{19}$ eV then we will find $R_{ns} = 0.71 \pm 0.063$. The deviation from the isotropy is $D_{ns} = (1 - 0.71)/0.063 = 4.6\sigma$.

If we estimate the N-S asymmetry R_{ns} by the formula (Ivanov, 1998)

$$R_{ns} = (n_1 - n_2)/(n_1 + n_2), \tag{4}$$

then the maximum deviation will be $R_{ns} = 0.295 \pm 0.065$ (Fig.3,(b), squares). The error $\delta R_{ns} = 0.065$ is determined by the formula

$$\delta R_{ns} = 2\sqrt{n_2(2n_2 + n_1)/(n_1 + n_2)^3} \tag{5}$$

The deviation is $D_{ns} = (0.497 - 0.295)/0.065 = 3.1\sigma$.

In Fig,3(b) triangles are data from (Ivanov, 1998). Unfortunately, in this paper the error δR_{ns} was found incorrectly and it led to the improper conclusion.

Fig.3 shows the ratio of the expected particle fluxes from the northern latitudes to the southern ones R_{ns} which are determined by the method of calculations of particles trajectories with the negative charge from the Earth in the galactic magnetic field (method of calculation see above). The calculation results are given for different energies of protons p (solid line) and iron nuclei Fe (dashed line). As seen from Fig.3, the N-S asymmetry can be explained if particles mainly are the iron nuclei.

Thus, the distribution of showers in galactic latitude and the north-south asymmetry can be explained in the framework of the galactic model of the origin of cosmic rays, where the main part of particles are the iron nuclei.

6 Conclusion

An estimation of the chemical composition of the primary radiation by the distribution of particles in galactic latitude shows that cosmic rays at E $\sim 10^{19}$ eV mainly are iron nuclei, their portion is $\geq 80\%$.

The north-south asymmetry in the distribution of cosmic rays at $\sim 10^{19}eV$ has been found.

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