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Influence of the Galactic Magnetic Field on Large-scale Anisotropies of Ultra-high Energy Cosmic Rays

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We present an analysis of effects of Galactic magnetic field on large scale structures in arrival directions of cosmic rays. Recent measurements of the Pierre Auger Observatory show a dipole pattern of arrival directions of cosmic rays above 8 EeV with amplitude $\sim 6.5\%$ pointing far ($\sim 125^\circ$) from the Galactic center. It demonstrates that these particles are of an extragalactic origin. We performed direct simulations of cosmic rays in CRPropa 3 propagated in the Jansson-Farrar model of the Galactic magnetic field. The large-scale patterns in the arrival directions of cosmic rays arising from an isotropic distribution of sources only due to the presence of the Galactic magnetic field were investigated for different scenarios of mass composition of cosmic rays. Arrival directions of simulated cosmic rays were investigated also for a dipolar distribution of sources outside the Galaxy with two directions of the injected dipole.

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1. Introduction

Ultra-high energy cosmic rays are thought to be of an extragalactic origin. This theory is supported by a recent measurement of a dipole anisotropy of cosmic rays with energies above 8 EeV by the Pierre Auger Observatory [1] that demonstrates that the direction of the measured dipole anisotropy in 3D with amplitude $\sim 6.5\%$ is far from the Galactic center ($\sim 125°$). The dipole amplitude in right ascension was found to be $\sim 4.7\%$. Before cosmic-ray particles reach an observer on Earth, they travel large distances between galaxies where they undergo interactions with the cosmic microwave background and extragalactic background light and they are also deflected in both extragalactic and Galactic magnetic field (GMF). The extragalactic magnetic filed is usually considered to be much weaker (orders of nanogauss) than the magnetic field of our Galaxy ($\sim \mu G$). The GMF is not yet well understood in detail but models describing its main parameters exist and are still being developed using measurements of Faraday rotations and synchrotron radiation [2].

In our research, we investigate the influence of the GMF on a flux of extragalactic cosmic rays of different mass compositions. Distributions of arrival directions in right ascension are studied for the case of an isotropic flux to the Galaxy and for a flux corresponding to the dipole distribution of sources in the direction of the recently measured dipole by the Pierre Auger Observatory and in the 2MRS dipole direction.

2. Simulation of particles

To simulate an isotropic flux of cosmic rays to the Galaxy, the Monte Carlo code CRPropa 3 [3] is used. A JF12 model of the GMF [2] is applied in simulations using regular, turbulent and striated components of the field. The JF12 is defined in a sphere of radius 20 kpc, with the Galactic center being in the center of the coordinate system. The observer with radius 100 pc is placed in our simulations in coordinates (-8.5,0,0) kpc, corresponding to the position of Solar system in our Galaxy. To achieve an isotropic flux to the Galaxy, particles are emitted isotropically from a sphere with radius 28.5 kpc with the center of the emitting shell placed at the position of the observer. In such settings, the flux from a unit solid angle in each direction with respect to the observer is constant. The scheme of the simulation arrangement is visualized in Figure 1. In order to check the correctness of the simulation settings, a simulation propagating protons to the observer without the presence of the GMF was performed as well.

We simulated three types of primary particles: protons, helium and nitrogen nuclei. Each primary is simulated with a power law energy spectrum with spectral index $\gamma = 3$. The energy range of simulated particles goes from 8 EeV up to 100 EeV. The energy losses on photon backgrounds are neglected since the energy loss lengths are much larger than the distance traveled by a particle in the Galaxy, even after deflections in the GMF. Each simulation starts with about 10^{10} injected particles. However, the number of particles reaching the observer is much smaller; for each primary the final number collected on the observer is about 250,000 particles.

Simulated particles follow an isotropic distribution of extragalactic sources. However, the observed anisotropies indicate a dipole character in arrival directions, therefore a dipole source distribution is probably more realistic. To investigate this scenario, our simulations are reweighted according to original positions of simulated particles. We inject a dipole with an amplitude of

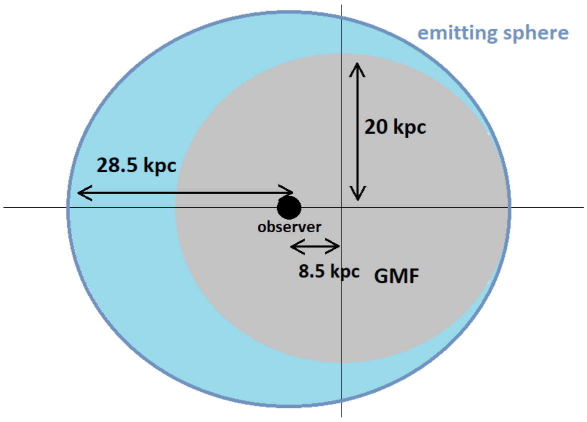

Figure 1: Scheme of the simulation settings.

0.065 in two directions. The first one is the direction of the dipole measured by the Pierre Auger Observatory pointing in Galactic coordinates to a direction ($\mathrm{l} = 233^\circ, \mathrm{b} = -13^\circ$) and the second injected dipole is in direction ($\mathrm{l} = 251^\circ, \mathrm{b} = 37^\circ$) corresponding to the 2MRS flux dipole measured by the the 2MASS Redshift Survey [4].

To summarize, we investigated three scenarios of distribution of arrival directions to our Galaxy: an isotropic flux, a dipole towards $\mathrm{l} = 233^\circ, \mathrm{b} = -13^\circ$ (Auger dipole) and $\mathrm{l} = 251^\circ, \mathrm{b} = 37^\circ$ (2MRS dipole).

3. Distribution of arrival directions in right ascension

Simulated events reaching the observer can be analyzed in right ascension α using the Rayleigh analysis [1]. The dipole amplitude r_α and phase φ_α are calculated using equations

$$r_\alpha = \sqrt{a_\alpha^2 + b_\alpha^2}, \tag{3.1}$$

$$\varphi_\alpha = \tan^{-1}\left(\frac{b_\alpha}{a_\alpha}\right), \tag{3.2}$$

where a_α and b_α are defined as

$$a_\alpha = \frac{2\sum_{i=1}^{N} w_i \cos(\alpha)}{\sum_{i=1}^{N} w_i} \quad \text{and} \quad b_\alpha = \frac{2\sum_{i=1}^{N} w_i \sin(\alpha)}{\sum_{i=1}^{N} w_i}, \tag{3.3}$$

where the sums go over all studied events N. The weight is equal to 1 for the analysis concerning an isotropic flux, while for a dipole source distribution the weight for each event is calculated as

$$w_i = A \cdot \cos(\delta_i) + 1, \tag{3.4}$$

where A is the amplitude of the dipole and δ_i is the angular distance of the original direction of the i^{th} particle from the direction of the injected dipole.

Distributions of arrival directions on the observer for proton, helium and nitrogen nuclei for the case of isotropic flux of cosmic rays to the Galaxy are depicted in Figure 2, Figure 3 and Figure 4, respectively. The plots contain the reconstructed dipole behavior from Rayleigh analysis together with the measured dipole by the Pierre Auger Observatory. The distribution of arrival directions in right ascension for the simulation without the presence of the GMF is shown in Figure 5. In this case, the distribution of arrival directions on the observer is compatible with isotropy with $\chi^2_{\mathrm{iso}}/\mathrm{ndf} = 10.2/11$, confirming correctness of the simulation settings.

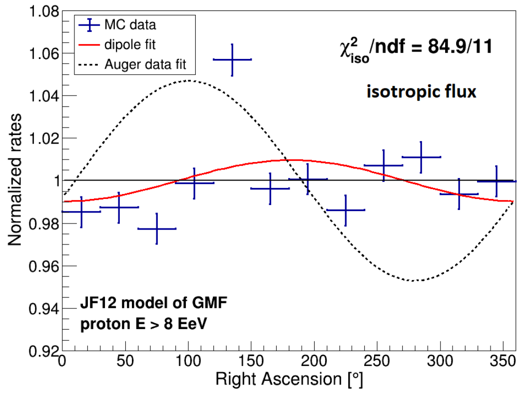

Figure 2: Distribution of arrival directions in right ascension of **protons** propagated in the JF12 field of the GMF with **isotropic flux to the Galaxy**.

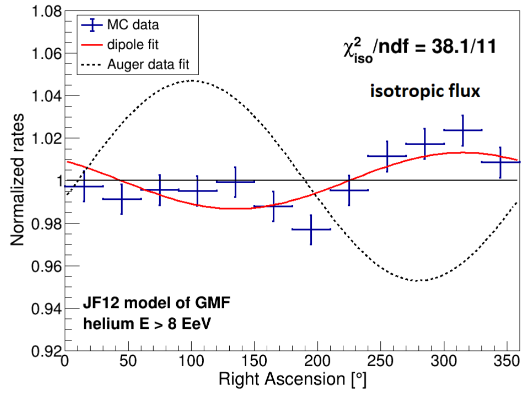

Figure 3: Distribution of arrival directions in right ascension of **helium nuclei** propagated in the JF12 field of the GMF with **isotropic flux to the Galaxy**.

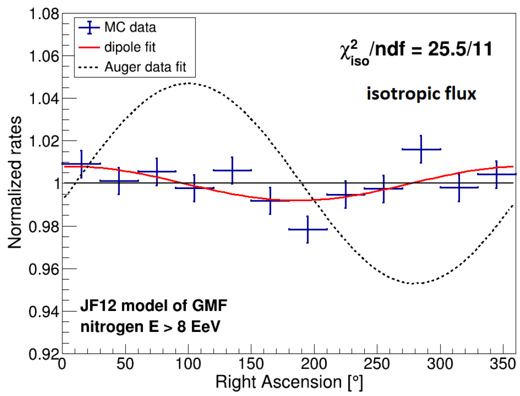

Figure 4: Distribution of arrival directions in right ascension of **nitrogen nuclei** propagated in the JF12 field of the GMF with **isotropic flux to the Galaxy**.

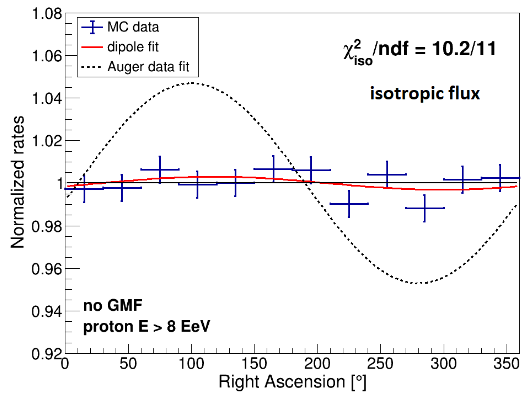

Figure 5: Distribution of arrival directions in right ascension of protons simualted **without the presence of the GMF**. The flux to the Galaxy is isotropic.

Distributions of arrival directions in the right ascension for protons, helium and nitrogen nuclei originating from a dipole source distribution with the amplitude 0.065 and the direction of the dipole in galactic coordinates $(l = 233^\circ, b = -13^\circ)$ and $(l = 251^\circ, b = 37^\circ)$ are shown in Figures 6

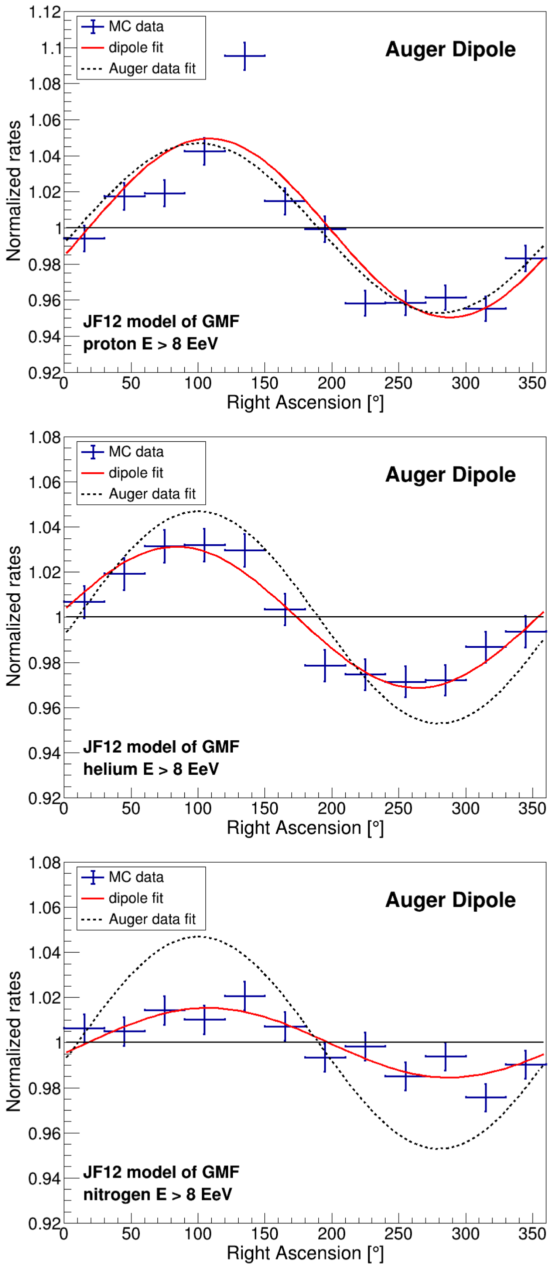

Figure 6: Distribution of arrival directions in right ascension of protons (top), helium (middle) and nitrogen (bottom) nuclei propagated in the JF12 model of the GMF with injected **Auger dipole** in $(l = 233°, b = -13°)$.

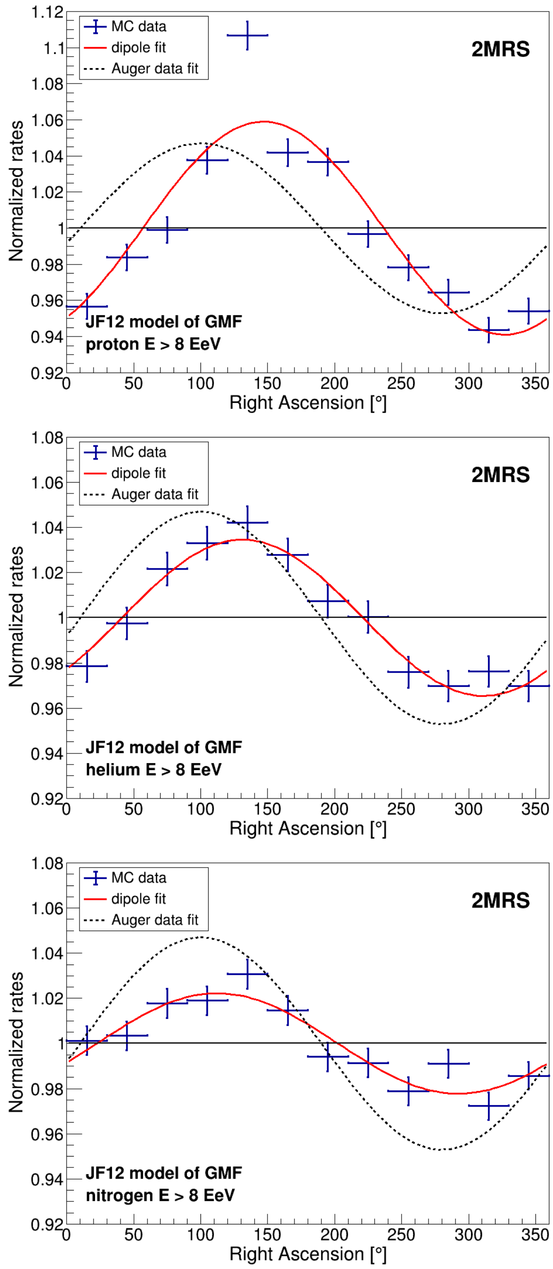

Figure 7: Distribution of arrival directions in right ascension of protons (top), helium (middle) and nitrogen (bottom) nuclei propagated in the JF12 model of the GMF with injected **2MRS dipole** in $(l = 251°, b = 37°)$.

and Figures 7, respectively. A Rayleigh analysis in the right ascension was performed. Calculated values of amplitudes and phases using equations (3.2) and (3.1) are listed in Table 1. A change of the amplitude on the observer with respect to the injected one can be determined using the simulation without the presence of the GMF. Relative change of the amplitude for both dipole directions as a function of the mean proton number of the primaries $\langle Z \rangle$ is depicted in Figure 8. A clear decreasing tendency of the amplitude with increasing mass composition $\langle Z \rangle$ (decreasing the rigidity of the particles) can be observed for both injected dipoles.

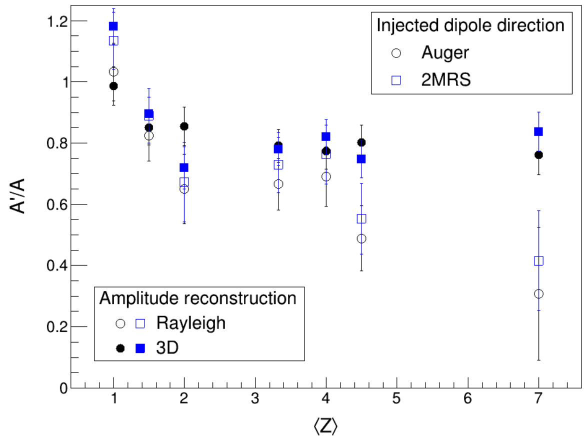

Figure 8: A relative change of the dipole amplitude (A') with respect to the original dipole amplitude of arrival directions (A) for different mass compositions of $\langle Z \rangle$ and two directions of the injected dipole.

4. Three dimensional dipole

The parameters of the three dimensional dipole were calculated according to [5] using the procedure of reconstruction with full sky coverage. The reconstructed direction of the dipole in Galactic coordinates l_d and b_d and its amplitude r for individual mass compositions and two injected dipole directions are listed in the last three columns of Table 1. The amplitude of the three dimensional dipole is not as influenced by the mass composition as the one in the right ascension, although a slight decrease can be observed in its evolution with proton number of primaries as well (see Figure 8).

It is interesting to look at the change of the direction of the dipole in the case of injected 2MRS dipole. This is visualized in Figure 9 where the direction of the original injected dipole is marked as a black point and individual colored arrows correspond to a change of the direction of the dipole for different mass compositions. The black star represents the direction of the measured dipole by the Pierre Auger Observatory. For pure proton composition the direction of the dipole moves away from the direction of the measured dipole by the Pierre Auger Observatory, however, for heavier primaries the direction of the dipole on the observer shifts towards the Auger one.

5. Conclusions

We investigated the influence of the GMF on a flux of cosmic rays above 8 EeV originating

primaries	dipole direction	$r_\alpha[\%]$	$\varphi_\alpha[^\circ]$	$r[\%]$	$l_d[^\circ]$	$b_d[^\circ]$
p	Auger	5.1 ± 0.4	108 ± 1	6.4 ± 0.3	219 ± 6	3.1 ± 2
He	Auger	3.2 ± 0.3	85 ± 3	5.6 ± 0.2	249 ± 5	-32 ± 4
N	Auger	1.5 ± 0.3	106 ± 11	4.9 ± 0.2	278 ± 3	-26 ± 4
p+He	Auger	4.1 ± 0.2	98 ± 1	5.5 ± 0.2	231 ± 5	-14 ± 3
p+N	Auger	3.4 ± 0.3	107 ± 2	5.0 ± 0.2	243 ± 4	-11 ± 3
He+N	Auger	2.4 ± 0.2	93 ± 3	5.2 ± 0.2	262 ± 2	-29 ± 3
p+He+N	Auger	3.3 ± 0.2	100 ± 2	5.1 ± 0.2	245 ± 3	-19 ± 3
p	2MRS	6.0 ± 0.4	-35 ± 1	7.6 ± 0.3	226 ± 6	43.2 ± 4
He	2MRS	3.6 ± 0.4	-49 ± 2	4.7 ± 0.2	249 ± 5	11.2 ± 2
N	2MRS	2.2 ± 0.3	-68 ± 5	5.4 ± 0.2	271 ± 2	-20.6 ± 3
p+He	2MRS	4.7 ± 0.3	-40 ± 1	5.8 ± 0.2	236 ± 4	31.4 ± 3
p+N	2MRS	4.1 ± 0.3	-45 ± 1	5.3 ± 0.2	248 ± 4	17.5 ± 2
He+N	2MRS	2.9 ± 0.2	-57 ± 2	4.9 ± 0.2	260 ± 2	-5.7 ± 2
p+He+N	2MRS	3.9 ± 0.3	-46 ± 1	5.1 ± 0.2	248 ± 3	15.3 ± 2

Table 1: Reconstructed amplitude r_α and phase φ_α of the dipole on the observer using Rayleigh analysis in right ascension for different primaries and two injected dipole directions outside of the Galaxy. r, l_d and b_d are calculated amplitudes and galactic longitudes and latitudes of the three dimensional dipole.

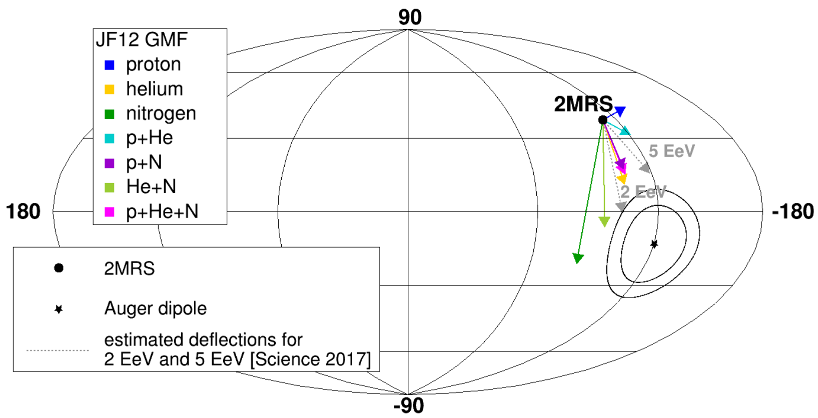

Figure 9: A change in the direction of the 3D dipole for different mass compositions of cosmic rays propagated in the JF12 model of the GMF. The injected dipole is the 2MRS dipole indicated as a black point. The black star represents a position of the direction of the measured dipole by the Pierre Auger Observatory [1] and contours indicate one and two sigma confidence regions of their measurement. The dashed gray arrows are estimated changes of the dipole position if the original dipole is in the 2MRS direction for particles of energy 10 EeV and rigidities 5 EV and 2 EV taken from [1].

from isotropic and dipole source distribution using simulations in CRPropa 3. Arrival directions of cosmic rays with different mass composition propagated in the JF12 model of the GMF were analyzed in the right ascension and using a three dimensional dipole. Two directions of the injected dipole outside the Galaxy were considered - a direction corresponding to the measured dipole by the Pierre Auger Observatory and a 2MRS flux dipole, both with amplitudes 6.5%.

The analysis of arrival directions of particles propagated in the JF12 model of the GMF reveals small deviations from isotropy on the observer depending on their rigidity; with heavier primaries having smaller discrepancies. These deviations afterwards propagate to the results concerning dipole source distribution.

Regarding the dipole source distribution, the amplitudes and phases of the dipole were reconstructed in the right ascension using Rayleigh analysis. The amplitude of the dipole on the observer level tends to decrease with decreasing rigidity of simulated cosmic rays for both studied cases. While for pure proton composition the amplitude remains almost the same as the injected one, for pure nitrogen composition the amplitude decreases down to 30%-40% of its original value.

The direction of the three dimensional dipole also changes after a propagation in the GMF. Amplitudes and directions of the dipole on the observer were calculated for different mass compositions and two directions of the injected dipole. The reconstructed amplitudes of the three dimensional dipole do not decrease as strongly with increasing mass composition $\langle Z \rangle$ as the amplitudes in the right ascension. In the case of the 2MRS dipole outside the Galaxy, the reconstructed direction of the dipole on the observer level moves almost in the opposite direction than the measured dipole by the Pierre Auger Observatory for pure proton composition. On the other hand, if we concern heavier primaries, the dipole on the observer shifts towards the measured direction.

6. Acknowledgement

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