Isotropization of Arrival Directions of Ultra-High Energy Cosmic Rays

Radomír Šmída*

Institute of Physics of the Academy of Sciences of the Czech Republic, Na Slovance 2, Praha

***Abstract*. The propagation of high-energy cosmic rays through interstellar turbulent magnetic fields is used to explain the measured isotropical arrival directions of cosmic rays up to the energy of 5×10^{19} eV. It was found that the observed isotropy of cosmic-ray arrival directions can be explained by the deviations of charged cosmic rays propagated through the Galactic magnetic field with a complex structure. Even a single source scenario of heavy nuclei below the above given energy can not be excluded. The isotropization of protons and light nuclei is possible only if they arrive from numerous sources unless extremely strong magnetic-field turbulences are present in interstellar space.**

***Keywords*: cosmic rays, magnetic field, propagation**

I. Introduction

Fruitful discussions about a possible connection between the positions of known active galactic nuclei and arrival directions of cosmic rays above the energy of 5.7×10^{19} eV have arised since the observation of the anisotropy at the Pierre Auger Observatory [1], [2]. Thereupon the influence of interstellar and intergalactic magnetic fields on the cosmic-ray propagation and the resulting angular deviations are extensively studied.

We assume that the deviations of cosmic rays in a magnetic field at the highest energies can be estimated by the explanation of the measured isotropy of the cosmic-ray arrival directions below the energy of 5×10^{19} eV [3], [4], [5], [6], [7], [8]. The Galactic magnetic field in interstellar space has two components – the regular[1] and the turbulent (random). Even if both of them can significantly bend the trajectories of ultra-high energy cosmic rays[2] (UHECRs) [9], only the influence of the turbulent magnetic fields on cosmic-ray propagation is studied in this article.

The deviations of the trajectories of cosmic rays with the energy less than 5×10^{19} eV in the Galactic magnetic field turbulences are considered as the source of the measured isotropy. We will look for such configurations of the turbulent magnetic fields in interstellar space which could sufficiently isotropized UHECRs. Only rough information about the sizes of the turbulent magnetic fields and the magnetic-field strengths are used to answer the following question: "*How strong and large must be magnetic-field turbulences to spread arrival directions of cosmic rays coming from one source with energies below* 5×10^{19} eV *over the whole celestial sphere?*".

II. Deviations of Cosmic Rays in Magnetic Fields

Unfortunately our knowledge of the Galactic magnetic field is so sparse that any firm conclusion cannot be made about cosmic-ray propagation even in the proximity of the Solar system. Despite of immense efforts during the last decade the lack of observational data about both the regular and the turbulent Galactic magnetic fields holds up to the present time [10], [11], [12]. Some model of the magnetic field has to be necessarily adopted if the propagation of cosmic rays is studied.

Several models of the regular magnetic field have been presented, but none of them can be favoured above the others by the current measurements [11]. It seems that the magnetic field in the Galaxy is rather complex with many turbulences than uniform over large scale. Furthermore the turbulent magnetic fields with the number of different sizes have been observed in the Galaxy, particularly close to the Galactic plane, but they are also expected in the halo. Many different mechanisms generating turbulent magnetic fields have been described as well. The current measurements of the turbulent magnetic fields in the Galaxy give 4 μG as the average strength of the magnetic field. The typical size L of the magnetic turbulences given in the literature is about 50 pc and possibly larger in the Galactic halo.

The gyroradius R_g is useful quantity for the description of the motion of charged particles in magnetic fields. It is defined as the radius of the circular motion of a charged particle in a constant magnetic field B. For a relativistic particle it equals to

$$R_\mathrm{g}[\mathrm{kpc}] \simeq \left(\frac{\Re}{10^{18}\ \mathrm{V}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)^{-1}. \qquad (1)$$

The rigidity $\Re$ is defined as the ratio of the total particle momentum times the speed of light and the particle electric charge Ze, where Z is the atomic number and e the elementary charge. The rigidity can be written as the ratio of the particle energy and its charge in the relativistic case, i.e. $\Re = E/Ze$. For example, a proton with the energy of $E = 10^{18}$ eV propagates much like an iron nucleus ($Z = 26$) with the energy $E = 2.6 \times 10^{19}$ eV through the same magnetic field.

[1] Defined as the component of the Galactic magnetic field which is nonzero after summing over a space with a size of 1 kpc.

[2] Defined here as cosmic rays with energies greater than 10^{19} eV, 1 eV $\simeq 1.602 \times 10^{-19}$ J.

Here, B is the strength of the perpendicular component of a constant magnetic field[3].

It can be shown that deviations of cosmic rays in the magnetic field become small if $R_g >> L$. However, the gyroradii of UHECRs are comparable with the sizes of magnetic fields in the energy range of our interest, particularly if primary cosmic rays are heavy nuclei. The trajectory of any charged particle becomes significantly deflected in a magnetic-field region if it has enough space to rotate by arbitrary angle, i.e. if $R_g \leq L$. The energy up to which cosmic rays can be randomized in interstellar space depends on the sizes and the strengths of the turbulent magnetic fields and also on the electric charge of cosmic rays.

The cosmic-ray propagation process in the interstellar space has been studied by many authors (e.g. [13], [14], [15]). We have adopted the backtracking method used in [16], which follows a trajectory of an individual particle. It can be applied for the modelling of the cosmic-ray propagation through the interstellar space if energy losses can be neglected. Instead of following a particle trajectory from the magnetic boundary of the Galaxy towards the Earth an anti-particle with the same energy is released from the Earth. The trajectory of propagated particle can be calculated by the integration of the equation of motion.

III. Description of Calculation

A particle with the rigidity $\Re$ was propagated from the starting point to the distance of L through a random magnetic field. Then new random magnetic field was generated in the space and the particle was propagated again from this point up to the distance of L. And so on until the particle travelled through the distance $N\ L$, where N is the number of spheres of the radius L filled with the random magnetic field B. The following values of L were used: 1, 5, 10, 25, 50, 100 and 150 pc. The number of spheres N gives the overall extension of the region filled with the magnetic-field turbulences and the radius L describes the size of the turbulences.

The scaling factor of the random magnetic field was uniformly distributed between 0.5 and 1.5 and thus its average equals to 1. The real values of the magnetic-field vector were calculated by the scaling of one of the following values: 1, 2, 4, 8 and 12 μG.

Finally, the particle rigidity ranges from 5×10^{17} V to 5×10^{19} V, which fully covers the energy of few 10^{19} eV for both light and heavy nuclei.

The equation of particle motion was integrated by the fourth-order Runge-Kutta method with the adaptive stepsize control according to [17]. For each trajectory the angular deviation between the starting and final velocity vectors and the propagated distance were calculated. Subsequently, basic statistical characteristics for a set of 10^5 testing particles were found, i.e. median, minimum and maximum, the 50th and 90th percentile.

[3]The unit of the magnetic-field strength is 1 μG = 10^{-10} T.

IV. Results and Discussions

The principal aim of this study is to find such configurations of turbulent magnetic fields that may isotropize cosmic rays. The deviation of cosmic rays at given rigidity in the magnetic field increases with the strength, size and number of turbulent magnetic fields along their path. Cosmic rays coming from one source are fully isotropized if the median of the angular deviations equals to $90°$. Smaller angular deviations are required for the isotropization of cosmic rays originating in numerous sources, but the actual values depend on the angular distance between the sources.

Other important quantity which can affect the angular deviations is the size of the magnetized region. The particles with arbitrary energy are not trapped in any magnetic-field turbulence in our simulations. Therefore, their propagated distances can be approximately considered as the size of the magnetized region. In this way the size of the magnetized region ranges from $10\ L$ to $10^3\ L$. If only a fraction of interstellar space is filled with the magnetic turbulences, the size increases correspondingly.

The angular deviations increase with the rigidity, cell's size L, the number of cells N (or equivalently with the overall size of region filled with the turbulences) and also with the magnetic-field strength B. Figures 1 and 2 show the examples of the results obtained in our simulations, where cells' size $L = 50$ pc and four magnetic-field strengths were used. These figures differ in the rigidities of testing particles. Figure 1 displays the angular deviations for the rigidity of 10^{18} V (which corresponds to the energy of 8×10^{18} eV in case of oxygen nuclei or $\sim 3 \times 10^{19}$ eV in case of iron nuclei). Figure 2 shows the same results for one order of magnitude larger rigidity (e.g. protons with the energy of 10^{19} eV).

UHECRs from one source can be isotropized only if they are heavy nuclei. Moreover, their paths throught the Galactic magnetic field turbulences with the strength larger than 2 μG must be longer than 10 kpc. It is possible for the extended magnetic-field halo or, eventually, for the source located at low galactic latitude. On the contrary, the protons coming from a single source, even if still significantly deflected, are isotropized only by the propagation through extremely strong and large turbulent magnetic fields (i.e. $N \geq 500$, $L \geq 100$ pc and $B \geq 8$ μG).

The required properties of the magnetic-field turbulences for the isotropization of cosmic rays naturally depend on the number of the sources. Heavy nuclei and even protons propagating from many sources through the magnetic-field turbulences can be sufficiently scattered. In such a way, the isotropy of their arrival directions observed at the Earth could be explained. Further randomization of cosmic-ray paths may be also caused by the combination of rather complex regular Galactic magnetic field with its turbulences. Moreover, the galactic sources of ultra-high energy heavy nuclei are possible

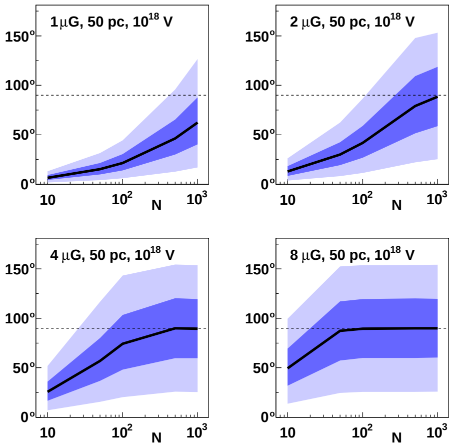

Fig. 1. Angular deviations for particles with rigidity of 10^{18} V as functions of the number of magnetized spheres with size $L = 50$ pc for four magnetic-field strengths. Black points show medians and darker (lighter) areas indicate results for the 50th (90th) percentiles. Dashed horizontal lines show $90°$.

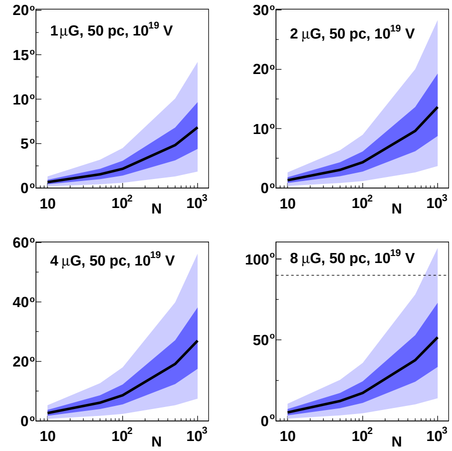

Fig. 2. Angular deviations for particles with rigidity of 10^{19} V as functions of the number of magnetized spheres with size $L = 50$ pc. For more details see caption to figure 1.

for some configurations of magnetic-field turbulences.

V. Conclusions

The isotropy of the arrival directions of UHECRs with the energy up to $\sim 5 \times 10^{19}$ eV observed at the Earth can be explained by the propagation of charged particles through the turbulences of the Galactic magnetic field. These turbulences of reasonable sizes and strengths may sufficiently widespread the scattering of arrival directions of any type of nuclei.

Moreover, the galactic sources of ultra-high energy heavy nuclei can not be excluded. The single source of the ultra-high energy heavy nuclei is possible if the paths of cosmic rays through strong interstellar magnetic-field turbulences (with typical sizes larger than 50 pc) are longer than 10 kpc.

Consequently, if heavy nuclei (e.g. iron nuclei) constitute the major part of the cosmic-ray flux then the angular deviations larger than $10°$ caused by the turbulent magnetic fields may be expected at the energies above 5×10^{19} eV.

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