Isotropization of Arrival Directions of Ultra-High Energy Cosmic Rays

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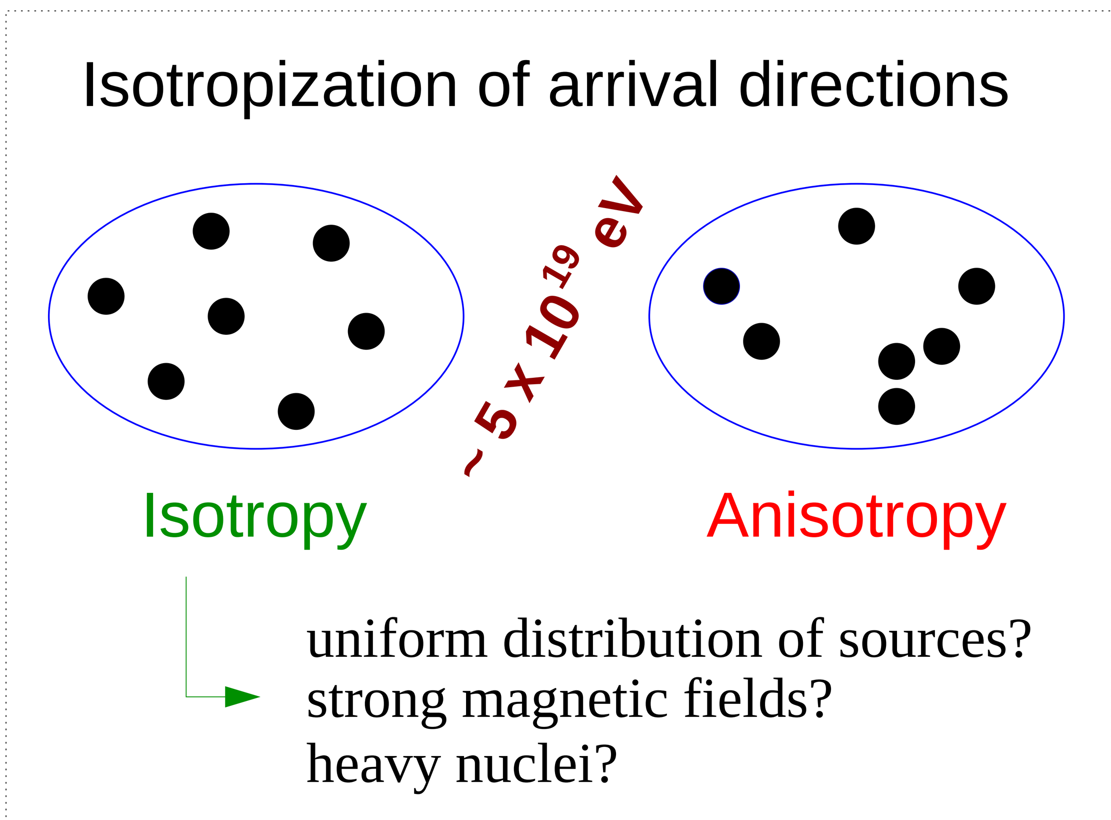
Abstract

The measured isotropy of arrival directions of cosmic rays up to the energy of 5×10^{19} eV is used to study cosmic-ray propagation through interstellar turbulent magnetic fields. A simple model of turbulent magnetic fields was applied for the calculation of particle trajectories in interstellar space.

It was found that the measured 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 energy of 5×10^{19} eV 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.

Cosmic-Ray Arrival Directions

The anisotropy of cosmic-ray arrival directions was measured at the Pierre Auger Observatory above $E = 5.7 \times 10^{19}$ eV [1, 2]. Can deviations of cosmic rays in magnetic fields explain the isotropy at lower energies [3, 4, 5, 6, 7, 8]?



Only rough information about typical size and strength of turbulent (random) magnetic fields in our Galaxy are used to answer a simple 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?*”.

Turbulent Magnetic Field in Galaxy

Galactic interstellar space is filled with rather complex magnetic field which has two components – regular (large-scale) and turbulent (random). Because of our limited knowledge about both fields [10, 11, 12] some model has to be used if cosmic-ray propagation is studied [9, 12].

The turbulent magnetic fields were observed close to the Galactic plane, but they are also expected in the halo. The current measurements of the turbulent magnetic fields give $\sim$ **4** μ**G** as the average strength of the magnetic field B in the proximity of the Sun. The typical size L of the magnetic-field turbulences is about **50 pc** and possibly larger in the Galactic halo [13, 14, 15, 16].

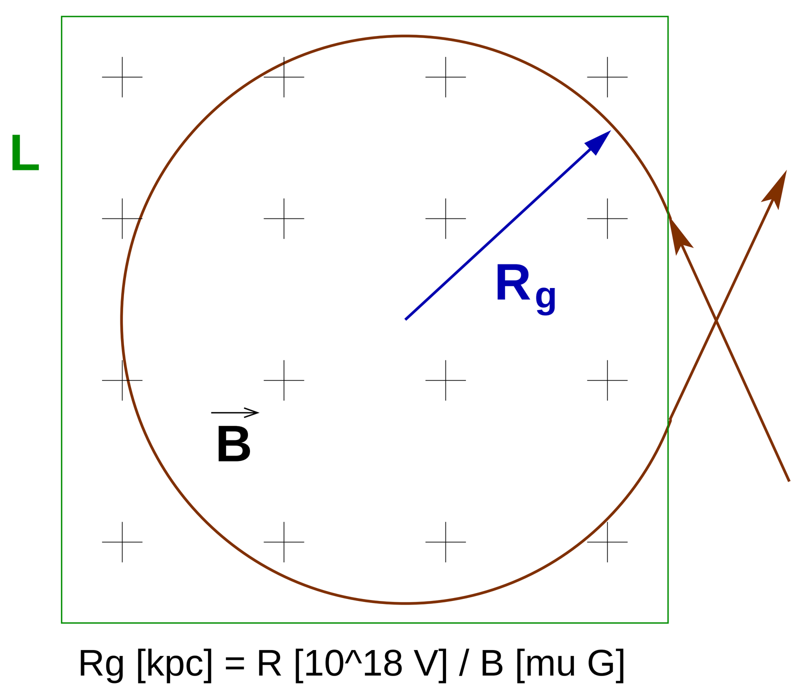


Figure 2: A charged particle becomes significantly deflected in a magnetic field with strength B and size L if $R_g \leq L$.

Description of Calculation

A particle with the rigidity $R = E/Ze$ was propagated from a starting point to a distance of L through a random magnetic field with a strength B. Then new random magnetic field was generated in a space and the particle was propagated again from this point up to the distance of L. And so on until the particle travelled through N spheres of a radius L filled with a random magnetic field (see figure 3).

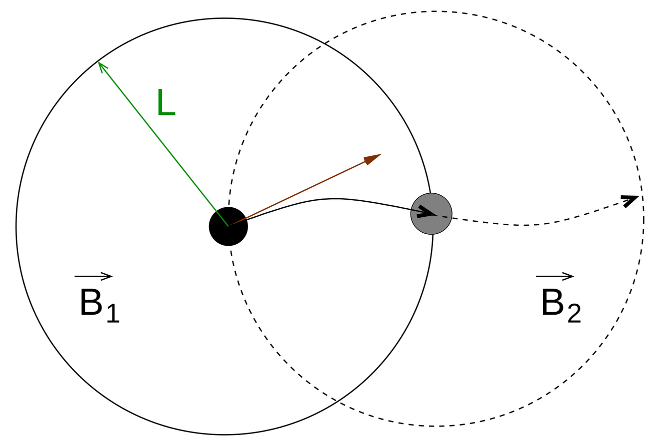


Figure 3: Sketch of propagation in our model.

The list of values used in our simulations:

- Rigidity: from 5×10^{17} V to 5×10^{19} V
- Magnetic-field strength: 1, 2, 4, 8 and 12 μG
- Cell's size: 1, 5, 10, 25, 50, 100 and 150 pc
- Number of cells: from 10 to 10^3

Results and Discussion

- 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 coming from numerous sources.
- Particles with the studied rigidities are not trapped in any magnetic-field turbulence and therefore their propagated distances can be approximately considered as the size of the whole magnetized region (i.e. NL).
- Heavy nuclei (see figure 4) from one source can be isotropized if their paths through the Galactic magnetic field turbulences with the strength larger than 2 μG are longer than 10 kpc.
- Protons and light nuclei (see figure 5) coming from a single source 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).
- Heavy nuclei and even protons propagating from many sources through the magnetic-field turbulences can be sufficiently scattered.
- Further randomization of cosmic-ray paths may be caused by the propagation through rather complex regular Galactic magnetic field.
- Galactic sources of ultra-high energy heavy nuclei are possible for some studied configurations of the magnetic-field turbulences.

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 the arrival directions of any type of nuclei in the case of numerous cosmic-ray sources.

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. Moreover, the galactic sources of ultra-high energy heavy nuclei can not be excluded.

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.

Angular Deviations

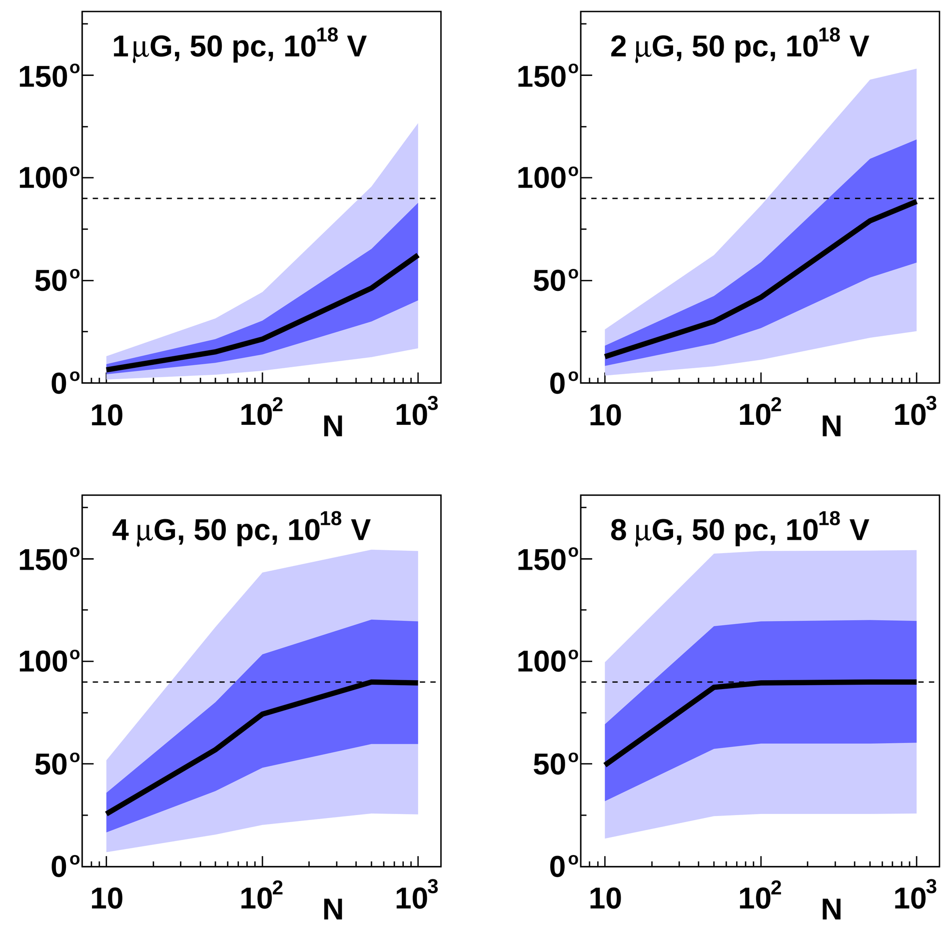


Figure 4: Angular deviations at rigidity of 10^{18} V as functions of number of magnetized spheres (with radius $L = 50$ pc) for four magnetic-field strengths. Black line shows median and darker (lighter) area indicates results for the 50th (90th) percentile. Dashed horizontal line shows 90°.

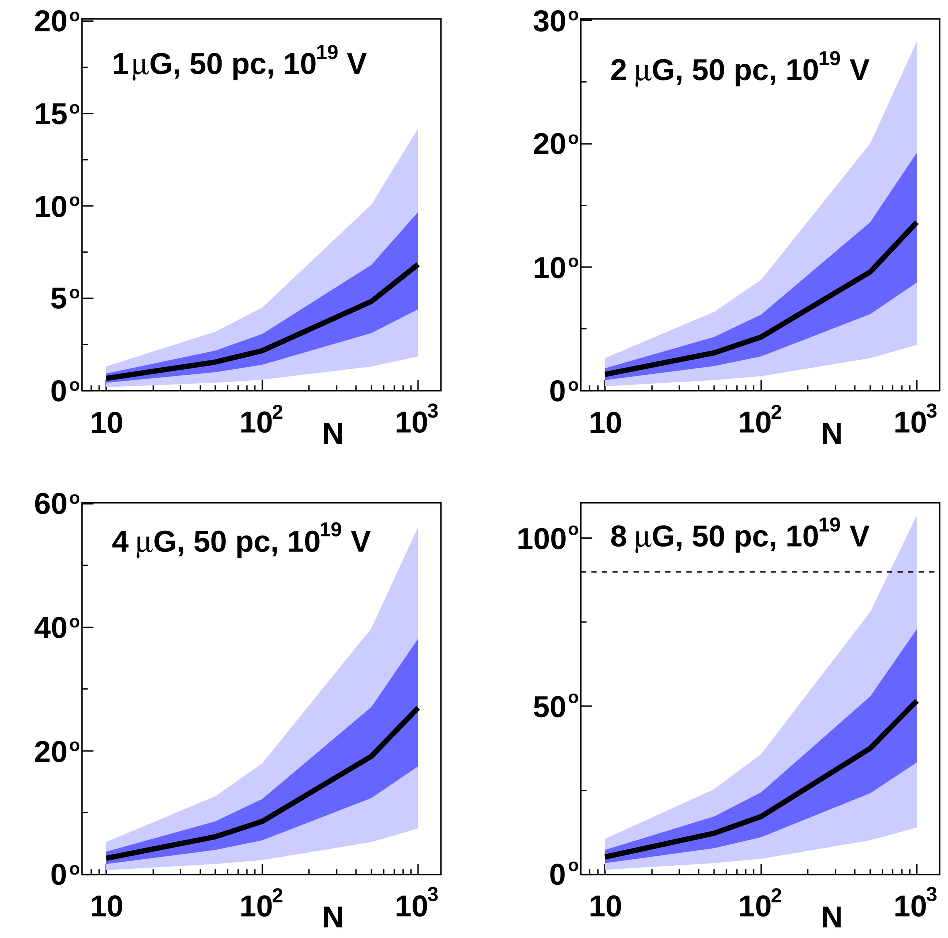


Figure 5: Angular deviations for particles with the rigidity of 10^{19} V as functions of the number of magnetized spheres with radius $L = 50$ pc. For more details see caption to figure 4.

Acknowledgements

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