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Arrival directions of ultra-high-energy cosmic rays assuming heavy mass composition

Alena Bakalová,[a,*] Ana Laura Müller[a] and Jakub Vícha[a]

[a] *FZU - Institute of Physics of the Czech Academy of Sciences,*
Na Slovance 1999/2, 182 00, Prague 8, Czech Republic

E-mail: bakalova@fzu.cz, mulleral@fzu.cz, vicha@fzu.cz

The arrival directions of cosmic rays are influenced by the Galactic and extragalactic magnetic fields, particularly in scenarios involving a heavy mass composition of primary particles. Following recent studies, we assume a pure iron composition of cosmic rays above 40 EeV and simulate their propagation in the Galactic magnetic field using the new UF23 base model. We analyze the expected arrival direction patterns on Earth assuming multiple source catalogues, including nearby active galactic nuclei or starburst galaxies. We compare the resulting patterns from the simulations with the published arrival directions of cosmic rays with energies above 40 EeV.

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1. Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) still remains one of the open questions in astroparticle physics, although recent measurements and studies are bringing new insights regarding their sources. The observation of a dipole anisotropy in the arrival directions of cosmic rays above 8 EeV [1] suggests their extragalactic origin. Furthermore, results of the Pierre Auger Observatory indicate a possible correlation of the arrival directions of UHECRs above $\sim$ 40 EeV with catalogues of extragalactic objects, including active galactic nuclei (AGNs) and starburst galaxies (SBGs), with the most promising correlation found for the starburst galaxy catalogue [2, 3].

Cosmic rays propagate long distances from their sources to the Earth and during their propagation they interact with the ambient photon fields in the Universe. These interactions lead to energy losses as well as possible changes in their mass composition. Furthermore, these processes restrict the horizon from which cosmic rays can arrive, with the horizon being strongly dependent on the energy and mass of the cosmic-ray particles. Additionally, as charged particles, cosmic rays are deflected by the magnetic fields in the Universe, including the Galactic magnetic field (GMF) and the extragalactic magnetic field (EGMF). Apart of the structure and strength of the magnetic fields, the level of the deflections depends on the energy and charge of the cosmic rays.

In this work, we investigate the patterns in the arrival directions of cosmic rays above 40 EeV from catalogue sources with the assumption of a pure iron nuclei composition. We consider three source catalogues including jetted AGNs, AGNs, and SBGs within 250 Mpc and show the predicted flux maps on the Earth taking into account deflections in the GMF. Simulations of cosmic-ray energy losses due to interactions with photon backgrounds are used to estimate the survival probabilities of iron nuclei reaching the Earth. Finally, we compare the predicted flux maps with public data on the arrival directions of cosmic rays above 40 EeV from the Pierre Auger Observatory [3], under our assumed mass-composition scenario.

It is important to note that the presented results are preliminary and may be updated as the analysis progresses.

2. Astrophysical model and simulations

2.1 Mass-composition model

We assume a pure iron nuclei composition of cosmic rays with energies above 40 EeV on the Earth. This extreme mass-composition scenario is motivated by the recent measurements of the first two moments of the shower maximum distribution by the Pierre Auger Observatory [4]. For detailed insights into the motivation for this mass-composition model see [5].

2.2 Catalogue sources

To investigate the patterns in the arrival directions of cosmic rays assuming iron nuclei above 40 EeV we use three source catalogues with objects up to a maximum distance 250 Mpc, as introduced by the Pierre Auger Collaboration in [3]. The first catalogue consists of 26 jetted AGNs from the Fermi 3FHL catalogue [6]. For this catalogue, we use the gamma-ray flux as a proxy for the cosmic-ray luminosity of individual sources, referred to as the γAGN scenario. Additionally, we adopt the approach proposed in [7], where the gamma-ray flux proxy is corrected by the Doppler boost factor D^{-4}, here referred to as the $\gamma D^{-4}AGN$ scenario. The second catalogue includes the AGNs from the Swift-BAT catalogue [8], referred to as *all AGNs* scenario, where the hard X-ray flux is used to estimate the cosmic-ray luminosity. Finally, we consider a catalogue of starburst galaxies, a subset from the catalogue by Lunardini et al. [9], with radio flux used as a weight for the UHECRs emission, the *SBG* scenario.

2.3 Propagation of cosmic rays in the Universe

The simulations of cosmic-ray propagation are divided into two separate parts. The first part focuses on the energy-loss processes of cosmic rays due to interactions with ambient photon fields in the extragalactic space, and the second one models their propagation through the GMF, where energy losses are neglected.

We simulate the propagation of the cosmic-ray iron nuclei from 40 EeV up to 170 EeV from various source distances using the CRPropa 3 code [10]. Energy losses on cosmic microwave background (CMB) and extragalactic background light (EBL), including the photo-pion production, electron-positron pair production, and photodisintegration, are taken into account. For the EBL, we adopt the Gilmore12 model [11]. A look-up table is generated using these one-dimensional simulations, which provides the survival probabilities of iron nuclei as a function of source distance and energy of the primary particle.

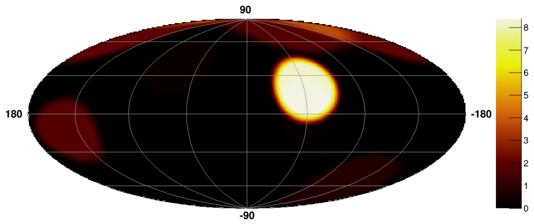
The propagation in the GMF is simulated again with the CRPropa 3 using the UF23 base model of the coherent component of the GMF [12] with the turbulent component from the JF12 model of the GMF [13] with corrections from the Planck Collaboration [14], hereafter referred to as JF12Planck. The correlation length of the turbulent field is assumed $l_c = 60$ pc. The EGMF is not explicitly included in the simulations. Instead, its effects are approximated by blurring of the arrival directions of cosmic rays at the edge of the Galaxy around the source direction with a blurring angle δ_{EGMF}.

In our simulations we adopt a power-law energy spectrum with spectral index $\gamma = 2.0$ with energies between 40 EeV and 170 EeV. However, the energy spectrum obtained on the Earth is re-weighted to follow the energy spectrum measured by the Pierre Auger Observatory from [15].

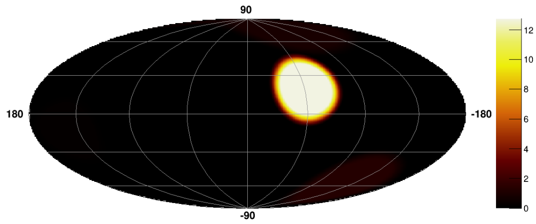
3. Results

3.1 Flux maps from catalogue sources

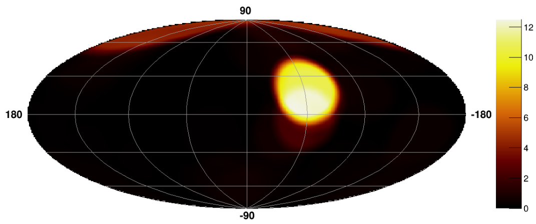
The predicted flux maps above 40 EeV at the edge of the Galaxy (without deflections in the GMF) are shown in Figure 1 for the four source catalogue scenarios. The attenuation of iron nuclei is taken into account, making the more distant objects less bright due to low probability of iron nuclei survival. Particles from each source are blurred around the source direction with a blurring angle $\delta_{\mathrm{EGMF}} = 5°$ (as an example) and the flux maps are smoothed with a 25° top-hat function. The dominant part of the flux originates from nearby sources. In the case of the three AGN scenarios, the dominant contribution comes from Centaurus A (distance of $\sim$ 3.7 Mpc). Despite the large gamma-ray flux of Markarian 421, this source is not strongly contributing in the γAGN scenario due to its large distance of $\sim$ 133 Mpc and therefore a low probability of iron nuclei survival. In the case of the SBG scenario, the dominant contribution is coming from NGC 4945 (distance of $\sim$ 3.5 Mpc), which is in similar direction as Centaurus A, and M82 (distance of $\sim$ 3.6 Mpc).



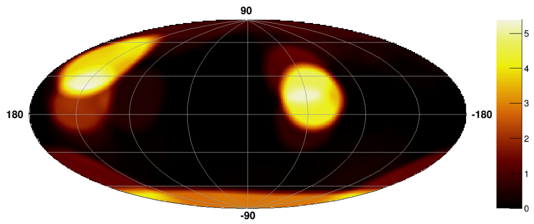
(a) γAGN



(b) γD^{-4}AGN

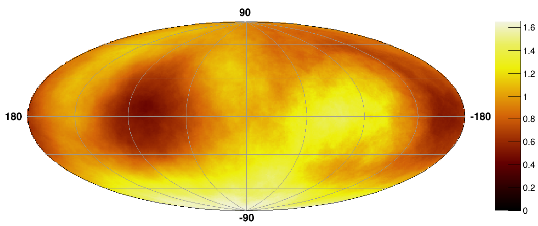


(c) all AGNs

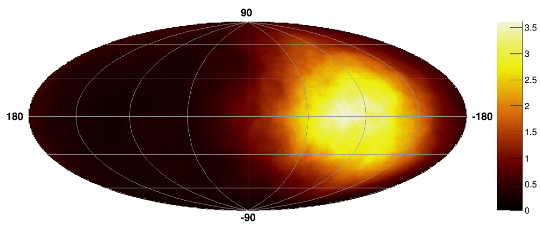


(d) SBGs

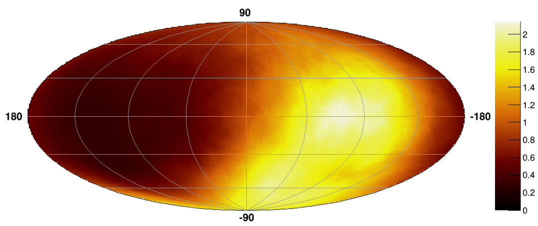
Figure 1: The predicted flux maps of cosmic rays above 40 EeV from source catalogues at the edge of the Galaxy, i.e. without the GMF, assuming pure iron nuclei with the effects of the attenuation from distant sources. The EGMF is considered with blurring angle $\delta_{\text{EGMF}} = 5°$ and the flux maps are smoothed by a 25° top-hat fucntion.



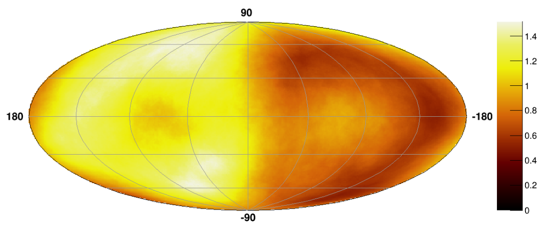
(a) γAGN



(b) γD^{-4}AGN



(c) all AGNs



(d) SBGs

Figure 2: The predicted flux maps on Earth of cosmic rays above 40 EeV from source catalogues assuming pure iron nuclei with the effects of the GMF, using UF23 base field with JF12Planck turbulent field and attenuation from distant sources. The EGMF is considered with blurring angle $\delta_{\text{EGMF}} = 5°$ and the flux maps are smoothed by a 25° top-hat function.

The flux maps on the Earth for individual source catalogue scenarios are visualized in Figure 2. Here, the deflections of the GMF are taken into account using the UF23 base model with the JF12Planck turbulent component. An EGMF blurring with $\delta_{\mathrm{EGMF}} = 5°$ is used and the flux maps are smoothed with a 25° top-hat function. A strong signal in the region of Centaurus A remains even after the propagation in the GMF for all three considered AGN scenarios. In the case of the SBG scenario a local excess is predicted close to the NGC 4945 direction. However, overall larger flux by a factor of ∼ 40% is predicted in the region of positive longitudes. This pattern emerges due to the strong contribution of the M82 and few additional sources, that are located far from the Galactic plane and their flux is not de-magnified due to the GMF. We note that these patterns are strongly dependent on the model of the GMF.

3.2 Correlation of the flux maps with arrival directions of UHECRs

We compare the predicted flux maps assuming pure iron nuclei above 40 EeV with the published arrival directions of cosmic rays above 40 EeV [3]. The predicted flux maps on the Earth for individual scenarios are reweighted according to the geometrical exposure of the surface detector array of the Pierre Auger Observatory [16]. We perform a likelihood ratio test of the arrival directions of cosmic rays with isotropy as a null hypothesis against a model composed of an isotropic background and a contribution from one of the four source catalogue scenarios with a fraction f_{cat}. We calculate the tests statistic defined as

$$TS = -2(\ln \mathcal{L}_{\mathrm{iso}} - \ln \mathcal{L}_{\mathrm{model}}), \tag{1}$$

where $\mathcal{L}_{\mathrm{model}}$ is the likelihood of the model scenario and $\mathcal{L}_{\mathrm{iso}}$ is the likelihood of the isotropic background. The TS is maximized using two free parameters, f_{cat} and δ_{EGMF}. The best fit parameters are listed in Table 1 for the three AGN scenarios. For the SBG scenario the obtained TS is consistently negative. The largest TS is obtained for the *all AGNs* model with signal fraction from catalogue sources of 17 % and blurring angle $\delta_{\mathrm{EGMF}} = 5°$.

Scenario	TS	δ_{EGMF}	f_{cat}
γAGNs	6.96	11°	25%
$D^{-4}\gamma$AGNs	6.65	8°	10%
all AGNs	8.27	5°	17%

Table 1: Parameters of the blurring angle δ_{EGMF} and catalogue fraction f_{cat} for the maximized TS of the AGN model scenarios.

4. Summary

We present flux maps of cosmic-ray arrival directions above 40 EeV on Earth from different source catalogues assuming pure iron nuclei. We take into account the attenuation of iron nuclei due to the interaction with CMB and EBL and the deflections in the GMF using the UF23 base model of the GMF with the turbulent component from the JF12 model with Planck-tuned parameters. The deflections due to the EGMF are modeled with a constant blurring factor δ_{EGMF}.

We compare the obtained flux maps with the arrival directions of cosmic rays above 40 EeV using a likelihood ratio test against isotropy. We maximize the TS with two free parameters, the catalogue fraction f_{cat} and the blurring angle δ_{EGMF}. The largest TS is obtained for the *all AGNs* scenario with $TS = 8.27$ suggesting a modest preference for this source distribution over isotropy. For the SBG scenario, a consistently negative TS values are obtained, indicating that this scenario does not provide a better fit than the isotropic model.

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References

[1] Pierre Auger collaboration, *Observation of a large-scale anisotropy in the arrival directions of cosmic rays above* $8 \cdot 10^{18}$ *eV*, *Science* **357** (2017) 1266–1270.

[2] Pierre Auger collaboration, *An Indication of Anisotropy in Arrival Directions of Ultra-high-energy Cosmic Rays through Comparison to the Flux Pattern of Extragalactic Gamma-Ray Sources*, *The Astrophysical Journal Letters* **853** (2018) L29 [1801.06160].

[3] Pierre Auger collaboration, *Arrival Directions of Cosmic Rays above 32 EeV from Phase One of the Pierre Auger Observatory*, *The Astrophysical Journal* **935** (2022) 170 [2206.13492].

[4] Pierre Auger collaboration, *Inference of the Mass Composition of Cosmic Rays with Energies from* $10^{18.5}$ *to* 10^{20} eV *Using the Pierre Auger Observatory and Deep Learning*, *Physical Review Letters* **134** (2025) 021001.

[5] J. Vícha et al., *A heavy-metal scenario of ultra-highe-energy cosmic rays*, in *Proceedings of the 7th International Symposium on Ultra High Energy Cosmic Rays*, vol. PoS(UHECR2024)123, 2025.

[6] Fermi-LAT collaboration, *3FHL: The Third Catalog of Hard Fermi-LAT Sources*, *The Astrophysical Journal Supplement Series* **232** (2017) 18 [1702.00664].

[7] C. de Oliveira, R. Guedes Lang and P. Batista, *On gamma rays as predictors of UHECR flux in AGNs*, *arXiv e-prints* (2024) arXiv:2408.11624 [2408.11624].

[8] K. Oh, M. Koss, C.B. Markwardt, K. Schawinski, W.H. Baumgartner, S.D. Barthelmy et al., *The 105-Month Swift-BAT All-sky Hard X-Ray Survey*, *The Astrophysical Journal Supplement Series* **235** (2018) 4 [1801.01882].

[9] C. Lunardini, G.S. Vance, K.L. Emig and R.A. Windhorst, *Are starburst galaxies a common source of high energy neutrinos and cosmic rays?*, *Journal of Cosmology and Astroparticle Physics* **2019** (2019) 073 [1902.09663].

[10] R. Alves Batista, J. Becker Tjus, J. Dörner, A. Dundovic, B. Eichmann, A. Frie et al., *CRPropa 3.2 - an advanced framework for high-energy particle propagation in extragalactic and galactic spaces*, *Journal of Cosmology and Astroparticle Physics* **2022** (2022) 035 [2208.00107].

[11] R.C. Gilmore, R.S. Somerville, J.R. Primack and A. Domínguez, *Semi-analytic modelling of the extragalactic background light and consequences for extragalactic gamma-ray spectra*, *Monthly Notices of the Royal Astronomical Society* **422** (2012) 3189 [1104.0671].

[12] M. Unger and G.R. Farrar, *The Coherent Magnetic Field of the Milky Way*, *The Astrophysical Journal* **970** (2024) 95 [2311.12120].

[13] R. Jansson and G.R. Farrar, *A new model of the Galactic magnetic field*, *The Astrophysical Journal* **757** (2012) 14.

[14] Planck collaboration, *Planck intermediate results. XLII. Large-scale Galactic magnetic fields*, *Astronomy and Astrophysics* **596** (2016) A103 [1601.00546].

[15] Pierre Auger collaboration, *Features of the energy spectrum of cosmic rays above 2.5 $\times 10^{18}$ eV using the Pierre Auger Observatory*, *Physical Review Letters* **125** (2020) 121106.

[16] P. Sommers, *Cosmic ray anisotropy analysis with a full-sky observatory*, *Astroparticle Physics* **14** (2001) 271.