

## Influence of Galactic magnetic fields on UHECR energy spectrum and mass composition on the Earth

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Considering source population, mass composition, and propagation in magnetic fields is important to reveal the origin of ultrahigh-energy cosmic rays (UHECRs). Currently, Telescope Array (TA) and Auger experiments have observed the energy spectrum, mass composition, and anisotropy of arrival directions at an ultrahigh-energy scale. On the other hand, the interpretation of these observables is strongly affected by model assumptions. In our previous works, we investigated the effect of the Galactic magnetic field (GMF) on the anisotropy of arrival directions through the analysis of the mock datasets and found that contributions of the starburst galaxy are underestimated. In this study, we apply the technique in previous studies and investigate the effect of GMF on the energy spectrum and mass composition. We especially discuss the discrepancy in energy spectrum between the northern and southern hemispheres reported by the TA and Auger experiments.

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## 1. Introduction

Telescope Array (TA) [1] and Auger experiments [2] lead ultrahigh-energy cosmic ray (UHECR) observations in the north and south sky, respectively. The major observational results of these experiments consist of the energy spectrum, mass composition, and anisotropy of arrival directions. The interpretation of these observables is important to constrain the origin of UHECRs.

There is a difference between the energy spectrum between TA and Auger experiments [3, 4]. Generally, the flux of UHECRs with the TA experiment is higher than that of the Auger experiment at all energy bins. Even after rescaling the energies of TA and Auger experiments with  $\pm 4.5\%$ , the flux of the TA experiment is higher than that of Auger at higher energy bins.

There are tries to explain the discrepancy of the energy spectrum: the first explanation for the discrepancy is the systematic uncertainties caused by the difference in detectors and reconstruction methods. However, [4] suggests that the difference in analysis methods does not affect the discrepancy between the TA & Auger energy spectrum. The second is an astrophysical origin that causes the discrepancy. For example, [5] suggests the local source in the northern sky, which can explain the higher CR flux of the TA experiment. Another explanation is what we propose in this report: the influence of the magnetic fields on the energy spectrum.

In our previous works [6, 7], we investigated the effects of the GMF deflection on UHECR anisotropies based on the calculation with CRPropa 3 [8]. The deflection of UHECRs caused by GMF affects the distribution of UHECRs. The limitation of sky coverage of the experiment also affects the analysis of the UHECR anisotropy.

In this study, we investigate the systematic difference in the energy spectrum caused by the Galactic magnetic field (GMF). For the source model, we assume the nearby starburst galaxies reported in [9, 10]. For the model of GMF, we adapt the JF12 model [11, 12] and PT11 model [13].

## 2. Method

### 2.1 Dataset generation without photodisintegration process

We mainly follow the dataset generation process in [6, 7]. If we ignore the GMF deflections, the CR flux outside the Galaxy can be written as

$$F_{\text{org}}(\mathbf{n}, \theta) = \frac{\sum_i f_i \exp(\mathbf{n}_i \cdot \mathbf{n} / \theta^2)}{\int_{4\pi} \sum_i f_i \exp(\mathbf{n}_i \cdot \mathbf{n} / \theta^2) d\Omega}. \quad (1)$$

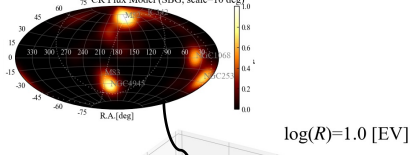
In this equation, the deflections by EGMF are approximated to be Gaussian smearing with the separation angular scale  $\theta$ . To reflect the deflection by GMF, we define the backtracked trajectories of CRs as

$$\mathbf{n}_{\text{org}} = A_{\text{BT}}(\mathbf{n}_{\text{earth}}, R), \quad (2)$$

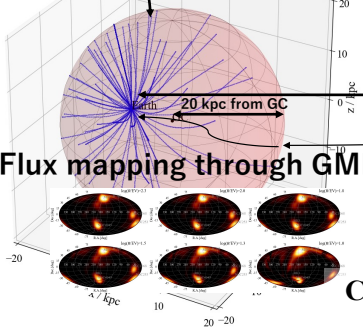
where  $A_{\text{BT}}$  represents the backtracking calculation through GMF models with CRPropa 3.2 [14]. For GMF models, we adapt JF12[11, 12] and PT11[13] models. The GMF models consist of a regular component and a random component. To focus on the difference at the highest energy bins,

# Dataset generation

① Calculation of CR flux outside the Galaxy (for each source)



② Flux mapping through GMF



① Calculation of CR flux outside the Galaxy for each source

② Flux mapping through GMF  
→ generation of CR flux on Earth (for each rigidity  $eR=E/Z$ )

③ 1D propagation for the distance  $D_i$  for each source

④ Choose the particle (E,Z,A) from the output ③  
⑤ Randomly determine the arrival direction based on the CR flux ②

③ 1D propagation for  $D_i$  energy loss

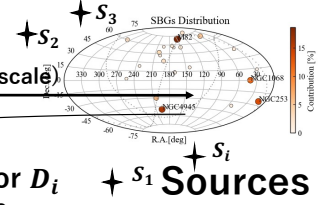
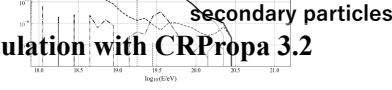


Figure 1: Dataset generation process.

we consider only regular components. We rewrite the Equation 1 as

$$\begin{aligned} F_{\text{earth}}(\mathbf{n}_{\text{earth}}, \theta, R) &= F_{\text{org}}(\mathbf{n}_{\text{org}}, \theta) \\ &= F_{\text{org}}(A_{\text{BT}}(\mathbf{n}_{\text{earth}}, R), \theta). \end{aligned} \quad (3)$$

For the energy spectrum on sources, we adapt a power-law spectrum with  $-2.7$  index and single-mass assumption (proton/nitrogen/iron). Although previous UHECR anisotropy studies [9, 10] assume the source contribution (anisotropic fraction) and isotropic backgrounds for UHECRs, we only assume the source contribution.

## 2.2 Dataset generation with photodisintegration process

To reflect the physical propagation process, we also apply 1-dimensional propagation with CRPropa 3.2 [14]. Figure 1 shows the dataset generation process. We add the 1-dimensional propagation with  $10^6$  primary CRs and randomly select the events whose energies are above energy thresholds.

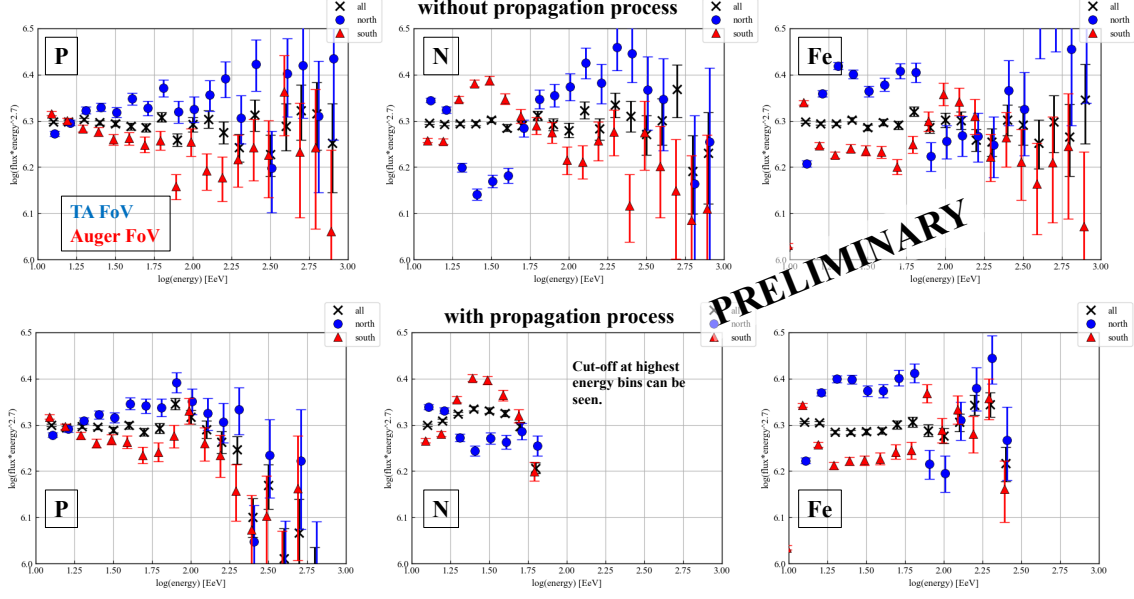
We conduct the propagation with the power-law spectrum in Section 2.2. We also test the datasets generated with a mixed-mass assumption [15]. We follow the formulas in [15]:

$$J_A(E) = \mathcal{J}_A f_{\text{cut}}(E, Z_A, R_{\text{max}}) n_{\text{evol}}(z) \left( \frac{E}{10^9 \text{ GeV}} \right)^{-\gamma}, \quad (4)$$

where  $J_A(E)$  is the energy spectrum of each mass ( $A$ ) on sources,  $n_{\text{evol}}(z)$  is a redshift evolution term (which is approximated to be 1), and  $f_{\text{cut}}$  is a cutoff function with maximum rigidity  $R_{\text{max}}$ , respectively. The cutoff function  $f_{\text{cut}}$  is given as

$$f_{\text{cut}} = \begin{cases} 1 & (E < Z_A R_{\text{max}}) \\ \exp\left(1 - \frac{E}{Z_A R_{\text{max}}}\right) & (E > Z_A R_{\text{max}}). \end{cases} \quad (5)$$

## Single-mass (proton/N/Fe, -2.7 index, $10^5$ events, JF12)



**Figure 2:** Energy spectrum of mock UHECR datasets with JF12 model. The top and bottom panels show the results without and with the propagation process, respectively. From left to right, each panel indicates single-proton, nitrogen, and iron assumption, respectively. The blue circle (red triangle) represents the results with the FoV of the TA (Auger) experiment.

Qualitatively the energy spectrum of each mass follows a power-law with an index of  $-\gamma$  at lower energies than  $Z_A R_{\max}$ , and follows the exponential cutoff at higher energies than  $Z_A R_{\max}$ . Same as in [6], we adapt the best-fit parameters from [15] as  $\gamma = -0.80$  and  $R_{\max} = 1.6$  EV.

### 3. Results and discussions

We show the results in Figures 2 and 3 for JF12 and PT11 models, respectively. In each figure, the top (bottom) panel shows the results with (without) the propagation process. From left to bottom, we assume single-proton, nitrogen, and iron case.

The difference between northern and southern sky largely depends on the regular component of GMF models.

For the JF12 case, the flux with TA sky coverage is larger than that with Auger sky coverage. In the single-nitrogen and iron case, the flux with Auger sky coverage is higher at the rigidity of  $\log(eR) \sim 0.6$  EV ( $\log(E) \sim 1.5$  EeV for single nitrogen case and  $\log(E) \sim 2.0$  EeV for single iron case). This may be because NGC1068 is outside of the TA FoV at this rigidity scale.

For the PT11 case, we can see similar effects as the JF12 case in the single-proton and nitrogen case. In the single-iron case, however, the flux with Auger sky coverage is much larger than that with TA experiment.

The photodisintegration process during the propagation affects the higher energy bins. Especially, the cutoff of the energy spectrum is clearly seen for the single-nitrogen case.

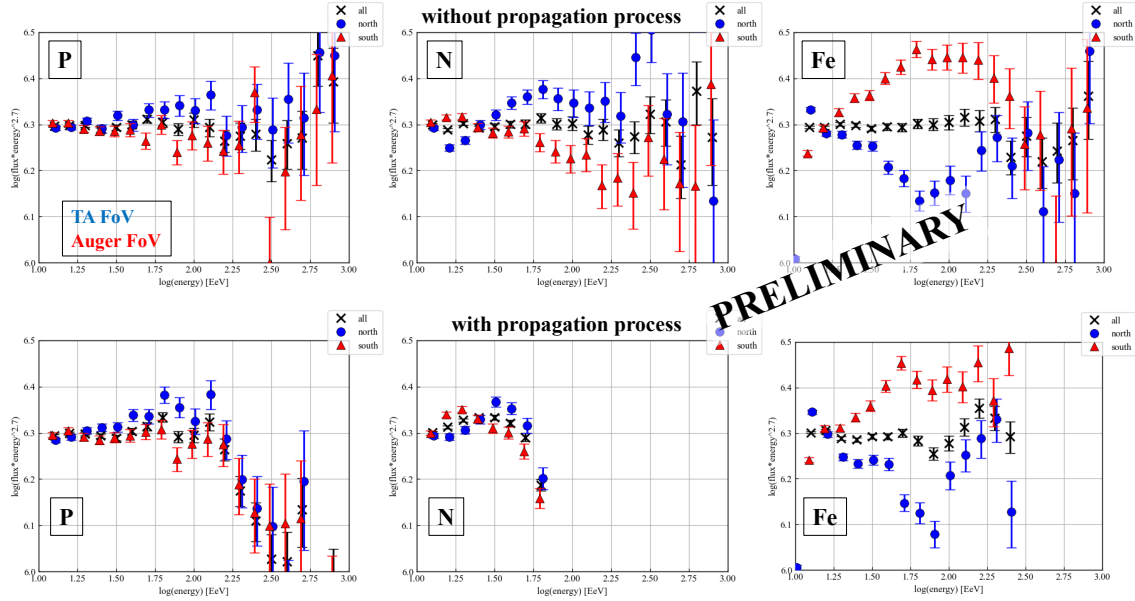
Single-mass (proton/N/Fe, -2.7 index,  $10^5$  events, PT11)


Figure 3: Same as Figure 2, but with PT11 model.

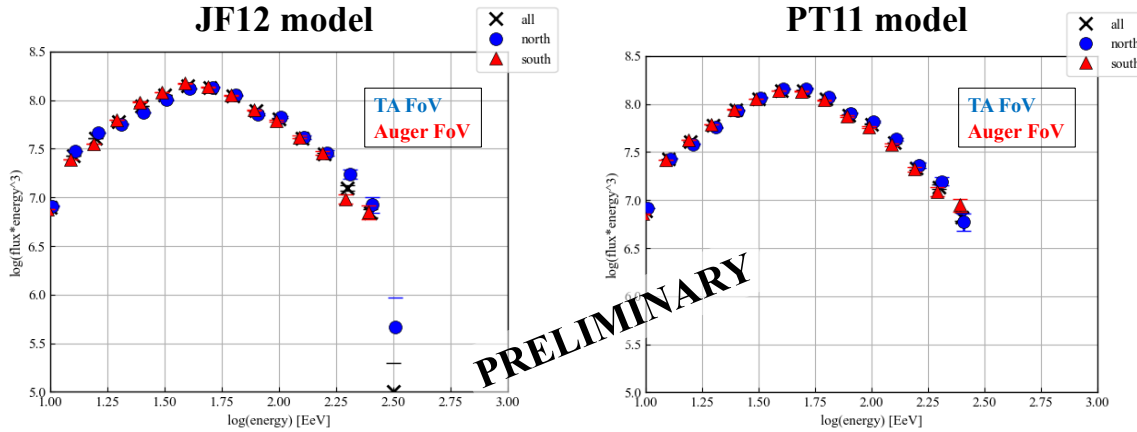
 Mixed-mass composition ( $10^6$  events)


Figure 4: Energy spectrum of mock UHECR datasets with mixed-mass assumption. The left panel and right panels indicate the JF12 model and PT11 models, respectively.

We also show the results for the mixed-mass composition case (photodisintegration process included). Due to the largest contribution of nitrogen, the results is similar to the single-nitrogen case. Below the cutoff of the spectrum, the flux of Auger is slightly higher than TA. At the highest energy bins, the flux of TA is larger than Auger. This is due to the energy loss of CRs from NGC1068 (for example, UHECRs whose energies are above 200 EeV cannot reach the earth over the  $\sim 18$  Mpc distance).

Although we can see the slight difference between TA and Auger sky coverage for the mixed-mass composition case, it does not explain all the differences between TA and Auger energy

spectrum.

#### 4. Summary

In this study, we investigate the systematic difference in the energy spectrum between TA and Auger experiments caused by the Galactic magnetic field (GMF).

Depending on the GMF model and the position of most contributed sources, the effects of GMF appear differently.

Especially when we care the photodisintegration process, the position of NGC1068 is important to the higher energy bins due to the large contribution and larger distance from the earth.

Although we can see the slight difference between TA and Auger sky coverage for the mixed-mass composition case, the deflection by GMF does not explain all the differences between TA and Auger energy spectrum.

We need to note that our assumptions and models are very simple and not realistic. Although we assume 100% contribution of nearby SBGs to UHECRs, [9] suggests only  $\sim 10\%$  of UHECRs can be explained by the SBGs. When we discuss the effects of magnetic fields in lower energy bins, we need to consider the random component of GMF models (although we focus on the highest energy bins in this report). The scattering by EGMF also needs to be energy-dependent: not like simple Gaussian scattering as in this study.

We also need to note that we assume the same energy spectrum and mass composition for all the SBGs. Especially, the shape of energy spectra of top-4 contributed SBGs (M82, NGC4945, NGC253, and NGC1068) should affect the difference in energy spectrum between TA and Auger experiments. For this scenario, we need to closely look at the astronomical origin considering the GMF deflections.

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