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Correlation Studies Between Ultra-high Energy Cosmic Rays and Fermi Gamma-ray Sources

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Abstract: We study possible correlations between ultrahigh energy cosmic rays (UHECRs) observed by Auger, AGASA and Yakutsk, and nearby active galactic nuclei (AGNs) and Fermi gamma-ray sources. The deflection effects by a new Galactic magnetic field (GMF) model are considered. A correlation between the Auger cosmic-ray events and nearby AGNs with a significance level of 4 sigma is found for the Auger UHECR data sets with or without deflection correction. Marginal correlations between the Auger events and Fermi gamma-ray sources, and between Auger/AGASA events and gamma-ray AGNs are found when the deflections calculated by the GMF model are considered. However, no correlation is found between the Yakutsk data and gamma-ray sources. Four gamma-ray loud AGNs, NGC 4945, ESO 323-G77, NGC 6951, and Cen A, within 100 Mpc have UHECR events within 3 degrees from their positions, which could potentially be cosmic ray accelerators. A large number of unidentified gamma-ray sources could also be UHECR source candidates.

Keywords: comic rays - gamma-rays - galaxies - magnetic fields

1 Introduction

The cosmic origin of ultrahigh energy cosmic rays (UHECRs) with energies $\geq 10^{19}$ eV (=10 EeV) are a long standing mystery in high-energy astrophysics. A theoretical distant limit for the cosmic rays with energies of $\sim 10^{20}$ eV travelling through the microwave background radiation field is called the GZK cut-off effect [6, 33]. Because of the GZK effect, particles with energies above 10 EeV are able to reach our Earth only from nearby sources within about 100 Mpc. This energy cut-off has been confirmed by recent cosmic-ray experiments [1, 21].

A barrier in the investigation of the UHECR origin is the deflections of UHECRs by the magnetic fields. Due to the poor knowledge of the extragalactic and intergalactic magnetic fields, the deflections of UHECRs by extragalactic and intergalactic magnetic fields have not yet understood. It is suggested that the deflections by extragalactic magnetic fields are generally less than 1° [3], but this issue is still in dispute. The Galactic magnetic fields (GMFs) are relatively better known [8, 28] and are widely discussed in the studies of UHECR origin [19, 25, 30]. The deflections of UHECRs by the GMFs cannot be neglected even for the protons of $E = 10^{20}$eV, since the deflection angles are comparable with the angular resolution of current experiments [16]. However, the previous studies have taken the older Galactic magnetic field morphology or the older (may wrong) magnetic field strength values for different components. For example, [19] tried seven GMF models to study the correlations between UHECRs and source populations. No halo component was included in the four GMF models they used and another three GMF models adopted from [28] have a strong halo component about 7 μG. Observational constraints on the Galactic magnetic field strength [9, 10], specially on halo magnetic field component and the configuration of disk magnetic fields [8] should be carefully considered in the GMF model.

Potential candidates for UHECR sources include pulsars, active galactic nuclei (AGNs) and subclasses of AGNs, even gamma-ray bursts. Correlation between nearby AGNs ($z < 0.018$) and Auger events have been reported [20, 21]. Very high energy γ-ray sources are possible UHECR accelerators. The $Fermi$ Large Area Telescope First Source Catalog (1FGL) contains 1451 γ-ray point sources [2]. Mirabal & Oya[18] investigated the correlation between 27 Auger UHECRs and 1FGL sources without considering the deflection by the GMFs and redshifts of $Fermi$ AGNs, and found no correlation between Auger events and Fermi sources. The correlations need more detailed analyzed after considering deflection of GMFs and GZK cut-off to probe this connection among the highest-energy phenomena in the Universe.

In this paper, we first construct a new GMF model based on the updated measurements of the Galactic magnetic fields and investigate the deflections of UHECRs by the GMFs. Considering the GZK cutoff and the deflection correction through our GMF model, we examine the possible correlation between UHECRs and nearby AGNs and $Fermi$ gamma-ray sources.

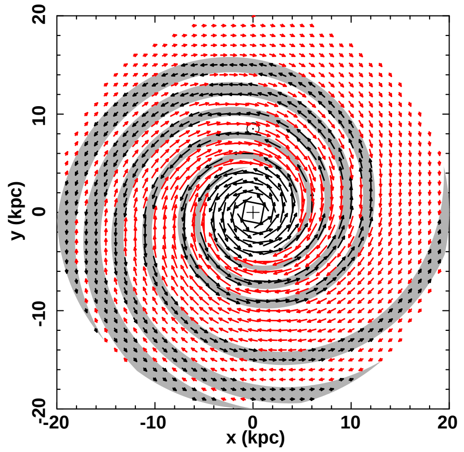

Figure 1: Configuration of Galactic disk magnetic field.

2 UHECR events

We collected public UHECR events which have good angular resolutions and energy information with energies higher than 40 EeV. Then we use the public data recorded by three experiments: Auger, AGASA, and Yakutsk, which cover both northern and southern hemispheres.

Auger is located in Argentina and began to collect data from 2004 January 1. From 2004 January 1 to 2007 August 31, 27 UHECR events with energies above 57 EeV were published [20]. Recently, updated data reported total 69 events with energies higher than 57 EeV [22]. Both AGASA and Yakutsk are located in the northern hemisphere. AGASA group published 57 events with $E > 40$ EeV [11]; Yakutsk collected 51 events with $E > 40$ EeV [24]. Due to the different angular resolution, different energy calibration, and different sky exposure for Auger, AGASA, and Yakutsk UHECR events, we search for the possible correlations separately between the three sets of UHECRs and astrophysical objects.

3 Deflection effects of Galactic magnetic fields

The GMFs have large-scale regular and small-scale turbulent components. The deflection angles of UHECRs caused by the turbulent fields are typically 1 order of magnitude smaller than that by the regular fields, so we ignore the turbulent component. The large-scale Galactic magnetic field is described by two components: disk component and halo component. We develop a toy GMF model based on updated measurements, e.g., rotation measures (RMs) of pulsars[8].

Magnetic fields in the disk are reversed from arms to inter-arms[8]. The radial profile of the field strength can be described as $B(R) = B_0 \exp(-(R - R_0)/R_B)$, where $B_0 = 2.1$ μG is the local field strength, R is the distance from the Galactic center, $R_0 = 8.5$ kpc is the galactocentric distance of the Sun, and the scale radius is $R_B = 8.5$ kpc. The four-arm model[13] is used in this work (see Fig. 1). The magnetic fields within 4.6 kpc do not have reversals. The initial width of each arm is set to be 0.4 kpc in our work. The pitch angle of the magnetic field is -11° as used by [8]. We should note that the field transition from the arms to the inter-arms is not smooth, and the influence of the bar in the Galactic center is not considered.

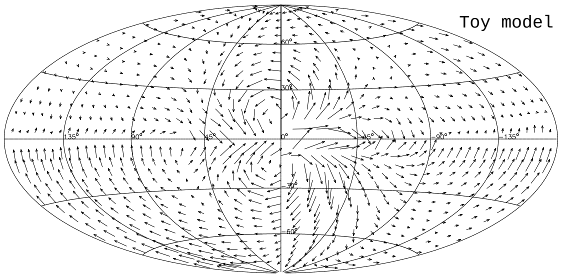

Figure 2: Deflection angle map of UHECRs with proton energy of 40 EeV by our toy model of Galactic magnetic fields.

The halo magnetic fields consist of a dipole poloidal field and a toroidal field with opposite directions above and below the Galactic plane. The field configuration was derived from the antisymmetric RM sky revealed by the extragalactic radio sources [7, 9] and the vertical filaments in the Galactic center [32]. The detailed descriptions on the dipole poloidal field and a toroidal field can be found in [15].

The cosmic rays are deflected in the GMFs by the Lorentz force. The net deflection can be approximated as[16]

$$\Theta \approx \frac{Z q_e}{pc} \int d\vec{l} \times \vec{B}_t \qquad (1)$$

where Zq_e is the charge of cosmic-ray particles, p is the momentum along the line of sight (LOS), and $\vec{B}_t$ is the field component perpendicular to the LOS. The integral is along the LOS from the source to the observer. In our work, the Hammurabi code [31] is used to calculate the all-sky deflections.

In Fig. 2, we present the deflection angle map of UHECRs for our toy GMF model. The composition of CRs is assumed to be proton, and the energy of proton is fixed to be 40 EeV. The disk field generates a strong deflection near the Galactic disk and in the high latitude. The toroidal field is similar to the disk field and has a large deflection near the disk, while the orientations are opposite above and below the disk. The dipole component has very strong deflections in the Galactic center region. The energy of observed UHECRs in our data sets varies from 40 EeV to more than 200 EeV. CR events with energy below 90 EeV are deflected by an angle $< 3^\circ$. The arrival directions of the events with energy above 90 EeV are deflected less than 2°[15]. The deflection angles are generally similar to the angular reso-

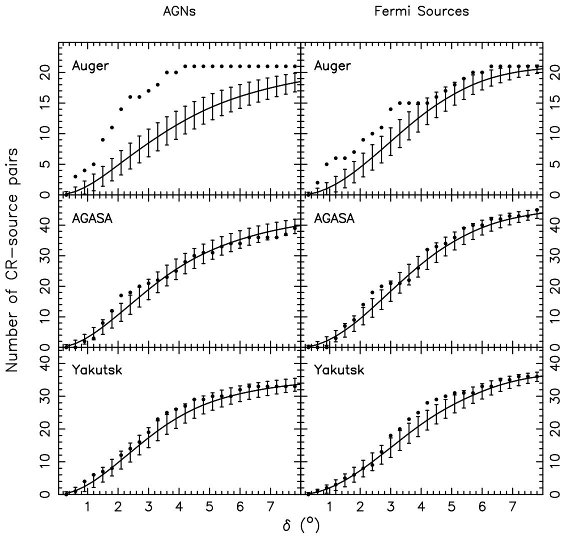

Figure 3: Number of UHECR-source pairs (dot) for nearby VCV AGNs (left column) and *Fermi* sources (right column), as a function of the angular separation (bin size) δ. The solid line is the Monte-Carlo simulated average number of UHECR-source pairs with error bar of $\pm 1\sigma$, derived from random isotropic distribution of simulated cosmic-ray events.

lution of the UHECR detectors ($\sim 1^\circ - 2^\circ$), so the GMF deflection correction is still desired in understanding the origin of UHECRs.

4 Correlation between UHECR events and Fermi sources

After correct of the deflections of the UHECR events by the GMFs, we search for possible correlations between three UHECR data sets (Auger, AGASA, and Yakutsk) and Fermi sources. The correlation method is the angular correlation function method [5, 29], i.e., counting the UHECR-source pairs with function of bin-size of angle (from $0^\circ - 10^\circ$). Chance probability evaluations is carried out using Monte-Carlo simulations. Distributions of CR location are constrained by exposure function of each experiments. The cosmic sources and UHECRs located at $|b| < 10^\circ$ are excluded in our analysis.

The previous correlation studies on UHECR-AGN have not considered the deflection effects of GMFs. For a test, we first do the correlations between three UHECR data sets and nearby AGNs. The correlation results between UHECRs and 830 nearby AGNs with $z < 0.024$ are shown in the left panel of Fig. 3. For the deflection-corrected Auger UHECRs by our GMF model, the chance probability is 2×10^{-5}, and the correlation significance is about 4σ, which is similar to but slightly less significant than the results of a chance probability of 1×10^{-6} and correlation significance of 4.7σ without deflection correction. As shown in Fig. 3 and Table 1, we found no correlation between the AGASA and Yakutsk events and AGNs.

High energy γ-ray emissions are thought to be a distinctive feature of the possible source of UHECRs [5]. We therefore investigate the possible correlations between $Fermi$ sources and the Auger/AGASA/Yakutsk UHECR events considering the deflection of the GMFs. In the analysis, we remove gamma-ray sources in 1FGL sources with redshift $z > 0.024$ by considering the GZK cutoff, and also neglect the sources located in the Galactic disk with $|b| < 10^\circ$. The correlation results for the *Fermi* γ-ray sources and UHECRs are shown in the right panel of Fig. 3. In the case of deflection-corrected Auger events by our GMF model, an excess appears around $\delta \sim 0.9^\circ$, with a chance probability of $P \sim 2.5 \times 10^{-3}$, and a significance level of $\sim 4.1\sigma$.

$Fermi$ sources contain several types of objects, such as pulsars, AGNs, and unidentified sources. It is interesting to see if possible correlations exist between some types of $Fermi$ sources and UHECRs. The correlation analysis results between the $Fermi$ AGNs, unidentified γ-ray sources and UHECRs are presented in Table 1. For comparison, we show the results of both including the deflection correction and no deflection correction. The $Fermi$ AGNs are weakly correlated with Auger/AGASA UHECRs after the deflection corrected by our GMF model.

4.1 Four nearby gamma-ray loud AGNs

$Fermi$ 1FGL catalog has 8 gamma-ray loud extragalactic sources of redshift $z < 0.024$. We found that 4 of these 8 objects have UHECR counterpart(s) within 3° from them after the deflections are corrected by our toy model. These four sources all belong to gamma-ray loud AGN class: NGC 4945, ESO 323-G77, NGC 6951, and Cen A.

The Cen A is the nearest FR II radio galaxy [14], which has been long proposed as a possible source of UHECRs [26]. Cen A was detected at MeV to GeV energies by the Fermi/LAT [2]. It was pointed that 4 of the 27 Auger events were possibly associated with Cen A [20, 21]. Piran [23] even suggested that Cen A is the only active potential source of heavy nuclei UHECRs within a few Mpc for the GZK cutoff after considering heavy composition.

NGC 4945 is identified as Seyfert 2 galaxy, also classified as starburst galaxy[17]. The radio non-thermal jet-like morphology is observed near the nuclei of NGC 4945[17]. ESO 323-G77 is classified as Seyfert 1 galaxy which has strong Fe II emission[4]. In X-rays, mildly relativistic outflows are discovered; the broadening Fe Kα line is detected, implying a Kerr black hole in the nuclei of ESO 323-G77. NGC 6951 is known as a LINER galaxy, and a bipolar radio outflow seems to be associated with the nuclear jet[27]. These jet-like features located in gamma-ray loud AGNs could have ability to accelerate protons or ion to ultra-high energies, but more observations and theoretic work are still needed.

		Auger Events			AGASA Events			Yakutsk Events		
sources	GMF	δ (°)	P	σ	δ (°)	P	σ	δ (°)	P	σ
VCV/AGN	Non	2.4	1×10^{-6}	4.7	1.4	0.066	1.8	3.0	0.420	0.4
	Toy model	3.6	2×10^{-5}	4.1	2.1	0.049	1.9	3.6	0.155	1.2
1FGL/All	Non	4.0	0.091	1.5	3.0	0.153	1.2	2.6	0.096	1.5
	Toy model	0.9	2.5×10^{-3}	4.1	2.4	0.070	1.7	4.2	0.053	1.8
1FGL/AGN	Non	7.6	0.013	2.4	3.8	0.025	2.2	5.2	0.416	0.4
	Toy model	0.9	0.037	3.1	2.7	7.0×10^{-3}	2.8	3.6	0.150	1.2
1FGL/Un-id	Non	7.0	0.100	1.5	6.0	0.201	1.0	2.6	0.038	2.1
	Toy model	3.0	0.021	2.4	5.4	0.196	1.0	6.6	0.015	2.2

Table 1: Correlations between three UHECRs events sets with AGNs and Fermi γ-ray sources with or without deflection corrections by GMFs. 1FGL/AGN implies the Fermi gamma-ray loud AGNs, and 1FGL/Un-id is the unidentified Fermi gamma-ray sources. δ is the separation angle of UHECR-source pair with a significant excess; P is the chance probability; σ shows the significance level.

5 Summary

We study correlations between three UHECR event sets and Fermi gamma-ray sources and nearby AGNs after the deflection of Galactic magnetic fields is considered. We construct a new toy Galactic magnetic field (GMF) model with the updated measurements. After considering the deflection correction, the correlation between nearby VCV AGNs and Auger events still exist. The Auger events show a marginal correlation with the Fermi gamma-ray sources. The weak correlations between Auger/AGASA events and Fermi AGNs is found. Four nearby gamma-ray loud AGNs which are located within 3° of UHECR events are potential candidates for production sites of UHECRs. The connection between a large number of unidentified gamma-ray sources and UHECRs may still exist, requiring further observations and studies.

In our analysis, the composition of UHECRs is assumed to be dominated by protons. The deflection of heavy UHECRs by the GMF models is proportional to the charge of nuclei, which leads to a very large deflection angle, and then any correlation discussed in this work can be diminished. In a summary, the understanding of UHECR origins requires more measurements of UHECR events and the knowledge of Galactic and extra-galactic magnetic fields.

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