Propagation of Ultra-high-energy Protons in Cosmic Magnetic Fields

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Abstract: We simulate the arrival distribution of ultra-high-energy (UHE) protons by following their propagation processes in several strengths of a structured extragalactic magnetic field (EGMF). Comparing our result to observational one by Akeno Giant Air Shower Array, we constrain the number density of UHE cosmic ray sources with the small-scale anisotropy. As a result, the source number density is \(\sim 10^{-5}\) Mpc\(^{-3}\) with uncertainty of about an order of magnitude due to the small number of observed events. This hardly depends on our structured EGMF strength. We also investigate future prospects for this approach. The near future observations, such as Pierre Auger Observatory, can distinguish \(10^{-4}\) and \(10^{-5}\) Mpc\(^{-3}\) accurately from the more source densities. Number of events to discriminate between \(10^{-4}\) and \(10^{-5}\) Mpc\(^{-3}\) is dependent on the EGMF strength.

Introduction

The origin of ultra-high-energy cosmic rays (UHE-CRs) is one of challenging problems in astroparticle physics. One of significant information on UHECR sources is their arrival distribution. Akeno Giant Air Shower Array (AGASA) reports small-scale anisotropy (SSA) within a few degree scale while large-scale isotropy (LSI) based on a harmonic analysis \(^1\)\[1\].

The SSA is predicted if UHECRs are of astrophysical origin with very small number. Therefore, the SSA has constrained their source number density to \(10^{-5}\) Mpc for no extragalactic magnetic field (EGMF) \[4, 5\] and \(10^{-6}\) Mpc for a simply uniform turbulent EGMF\[6\].

Recent simulations of cosmological structure formation predict structured magnetic fields \[7, 8\] which roughly trace the baryon density distribution. Thus, the EGMF is also structured. In last year, we discussed the propagation of UHE protons in a structured EGMF that reproduces the observed local structure \[9\], and the arrival distribution. However, we discussed only one EGMF strength, which is normalized to \(0.4\mu\)G at the center of the Virgo cluster. Observations of magnetic fields in a cluster have large uncertainty in the range of \(0.1\) - a few \(\mu\)G \[10\]. Thus, it is very important to investigate the propagation and constraints on UHECR sources in several strengths of the EGMF.

In this study, we discuss the propagation of UHE protons in several strengths of the EGMF and a Galactic magnetic field (GMF), and compare the resulting arrival distributions with observational results by AGASA. From the comparison, the number density of UHECR sources is constrained. Such constraint has large uncertainty due to the small number of observed events at present. So, we also discuss the possibility of a decrease in the uncertainty with future observations.

Numerical Methods & Model

The propagation of UHE protons is calculated by an application of the backtracking method, which

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1. Such AGASA results conflict with High Resolution Fly’s eye (HiRes) reports, which finds no significant SSA \[2\]. However, this discrepancy is not statistically significant due to the small number of observed event \[3\].
is a method developed in our paper [9]. It is very insufficient to calculate their propagation forward since cosmic rays do not always reach the Earth under finite EGMF even if they are injected toward the Earth from their sources.

Our models of the source distribution and a structured EGMF are constructed out of the Infrared Astronomical Satellite Point Source Catalogue Redshift Survey (IRAS PSCz) catalog of galaxies[11]. This catalog has very large sky coverage (about 84% of all the sky). Thus, our source distribution and EGMF structure reflect large scale structures actually observed within 100 Mpc. The EGMF strength is normalized at the center of the Virgo cluster to $0.0, 0.1, 0.4$ and $1.0 \mu G$. Outside 100 Mpc, EGMF is assumed to be an uniform turbulence with $1nG$ and the source distribution is isotropic. More details are written in reference [9].

In this study, we adopt only a source model that all sources have the same power. In conclusion, we discuss results from another simple source model, which power of each source is proportional to its luminosity.

Results

As written above, the arrival distribution has important information on UHECR sources. We investigate the number density of UHECR sources which can best reproduce the AGASA results. Our calculated arrival distributions are compared to the observed arrival distribution with the two-point correlation function

$$N(\theta) = \frac{1}{2\pi|\cos \theta - \cos(\theta + \Delta \theta)|} \sum_{\theta \leq \phi \leq \theta + \Delta \theta} 1[\text{sr}^{-1}],$$

(1)

which is an indicator of SSA. Number of cosmic ray events is set to 49 events in the energy range of $4 \times 10^{19} < E < 10^{20}$ eV. For the comparison, we define $\chi_{\theta_{\text{max}}}^2$ as

$$\chi_{\theta_{\text{max}}}^2 = \frac{1}{\theta_{\text{max}}} \left( \sum_{\theta = 0}^{\theta_{\text{max}}} \frac{[N(\theta) - N_{\text{obs}}(\theta)]^2}{\sigma(\theta)^2} \right),$$

(2)

where $N(\theta)$ is the two-point correlation function and $\sigma(\theta)$ is $1\sigma$ error due to the finite number of events. Small $\chi_{10}^2$ provides good agreement with the observational result.

$\chi_{10}^2$ are shown in figure 1. While the source number density with $10^{-7}$ Mpc$^{-3}$ results in larger value, the others are consistent with each other within $1\sigma$ statistical error. Hence, only the SSA cannot constrain the source number density sufficiently.

The arrival distribution must also satisfy the LSI. We calculate the two-point correlation function again, but from merely source distribution to be able to predict LSI observed by AGASA. This is figure 2.

In figure 2, the middle panels are the number densities that best reproduce AGASA results. However, source number densities an order of magnitude more than those of the best fit are consistent with the observation within $1\sigma$ error except $B = 0.0 \mu G$. On the other hand, almost all of source distributions with $10^{-7}$ Mpc$^{-3}$ cannot satisfy the LSI. For $B = 1.0 \mu G$, there is no source distribution in 100 source distributions. This fact can be understood in figure 1. Thus, the source number density that can best reproduce the AGASA result is $10^{-4} \sim 10^{-5}$ Mpc$^{-3}$ for $B = 0.0, 0.1 \mu G$, and $10^{-5} \sim 10^{-6}$ Mpc$^{-3}$ for $B = 0.4, 1.0 \mu G$ with
Figure 2: The two-point correlation functions calculated from only source distributions that can predict the LSI. The histograms are the AGASA result within $4 \times 10^{19} < E < 10^{20}$ eV (49 events). The error bars are from the event selection for the finite events and the shaded regions show total $1\sigma$ statistical errors. The GMF is included.

uncertainty of about one order of magnitude. The source density hardly depends on EGMF strength since 95% of space within 100 Mpc has not magnetic field.

The SSA and the LSI enable us to constrain the source number density. However, it has large uncertainty which originates probably from the small number of observed events. Therefore, one of our next interests is how small the uncertainty becomes at the Auger era.

In order to investigate this, it is necessary to compare our arrival distributions with future observational results, which, of course, cannot be known. In this study, an isotropic arrival distribution is adopted as a template for the future results. If UHECR sources are of astrophysical origin and have a small number density, the SSA becomes stronger. In this viewpoint, we compare our results of the simulation to an isotropic distribution, using the two-point correlation function.

200 event observation allows us to discriminate $10^{-5}$ and $10^{-6}$ Mpc$^{-3}$ with good accuracy since it can separate the distributions. This event number is probably comparable with current status of Auger. Detection of more events can divorce distributions with $10^{-4}$ and $10^{-5}$ Mpc$^{-3}$. When 500 events are observed, the number densities of $10^{-4}$ and $10^{-5}$ Mpc$^{-3}$ are perfectly separated if EGMF does not exist or is very weak.

Figure 3 shows distributions of $\chi^2$ defined as

$$\chi^2 \equiv \frac{1}{\bar{\theta}_{\text{max}}} \sum_{\theta=1}^{\bar{\theta}_{\text{max}}} \frac{[N_{\text{sim}}(\theta) - N_{\text{iso}}(\theta)]^2}{\sigma_{\text{sim}}(\theta)^2 + \sigma_{\text{iso}}(\theta)^2}. \quad (3)$$

This value represents the goodness of the fitting. The upper panels show current status corresponding to the AGASA result. The three distributions with $10^{-4}$, $10^{-5}$ and $10^{-6}$ Mpc$^{-3}$ are almost overlapped. The determination of the number density has large uncertainty.
Conclusions

In this study, we constrain number density of UHECR sources with the SSA in several strengths of EGMF and investigate future prospects for this approach. At the AGASA era, the source number density is \(~10^{-5}\) Mpc$^{-3}$ with uncertainty of about an order of magnitude due to small number of observed events. That near future observations increasing observed event number can improve its uncertainty. 200 event observation above \(4 \times 10^{19}\) eV can distinguish \(10^{-6}\) Mpc$^{-3}$ from the more source density. This event number is consistent with the number observed by Auger until this summer! More event detection enables us to estimate the source number more accurately and, then, to be easy to compare it with that of known powerful objects. Number of events to discriminate between \(10^{-4}\) and \(10^{-5}\) Mpc$^{-3}$ is dependent on the EGMF strength. Finally, we discuss results of another source model that power of each source is proportional to its luminosity, as discussed in [9]. The latter model predicts \(10^{-4} \sim 10^{-5}\) Mpc$^{-3}$ at present. The source number density increases since dark sources are also counted, but hardly contribute the arrival cosmic rays. More observation can discriminate \(10^{-3}\) Mpc$^{-3}$ from less number densities. This model has an additional degree of freedom by luminosity, compared with the former model. This provides large dispersion to distribution of \(\chi^2\). Therefore, \(10^{-4}\) and \(10^{-5}\) Mpc$^{-3}$ cannot be distinguished even at 500 event observations.

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References

[1] Takeda M. et al., ApJ, 522, 225, 1999
[2] Abbasi R.U. et al., ApJ, 610, L73, 2004
[3] Yoshiguchi H., Nagataki S., and Sato K., ApJ, 614, 43
[4] Blasi P., & de Marco, Astropart. Phys., 20, 559, 2004
[5] Kachelriess, M. & Semikoz, D., Astropart. Phys., 23, 486
[6] Yoshiguchi H. et al., ApJ, 586, 1211 (erratum: 601, 592)
[7] Sigl G., Miniati, F., and Ensslin, T.A., Phys. Rev. D, 70, 043007
[8] Dolag, K. et al., JCAP, 0501, 009
[9] Takami H., Yoshiguchi H., and Sato K., ApJ, 639, 803 (erratum: 653, 1584), 2006
[10] Vallee J.P., New AR, 48, 763, 2004
[11] Saunders W., et al., MNRAS, 317, 55, 2000