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

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Abstract: We simulate 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 number density of UHE cosmic ray sources with the small-scale anisotropy. As a result, the source number density is $\sim 10^{-5}\ \mathrm{Mpc}^{-3}$ with uncertainty of about an order of magnitude due to small number of observed events. This hardly depends on our structured EGMF strength. We also investigate future prospects for this approarch. The near future observations, such as Pierre Auger Observatory, can distinguish $10^{-6}\ \mathrm{Mpc}^{-3}$ obiviously from the more source density. More observations are going to decrease the uncertainty in the more source densities.

Introduction

The origin of ultra-high-energy cosmic rays (UHECRs) 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 the small-scale anisotropy (SSA) within a few degree scale while the large-scale isotropy (LSI) based on a harmonic analysis [1] [3].

The SSA is predicted if UHECRs are of astrophysical origin with very small number. Therefore, the SSA has constrained their source number density to $10^{-5}\ \mathrm{Mpc}$ without extragalactic magnetic field (EGMF) [4, 5] and $10^{-6}\ \mathrm{Mpc}$ with simply uniform turbulent EGMF[6].

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

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

Numerical Methods & Model

Propagation of UHE protons is calculated by an application of the backtracking method, which is a method developed in our paper[9]. It is very insufficient to calculate their propagation forward since

1. Such AGASA results conflict with High Resolution Fly's eye(HiRes) reports, which finds no significant SSA [1]. However, this discrepancy is not statistically significant due to the small number of observed event [2].

cosmic rays do not always reach the earth under finite EGMF even if they are injected from a source to the earth.

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, the source distribution and EGMF structure reflect large scale structures actually observed within 100 Mpc. Strength of the EGMF is normalized at the center of the Virgo cluster to $0.0, 0.1, 0.4$ and 1.0 μG. Outside the 100 Mpc, EGMF is assumed to be an uniform turbulence with 1nG and the source distribution is isotropic. More details are written in ref [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.

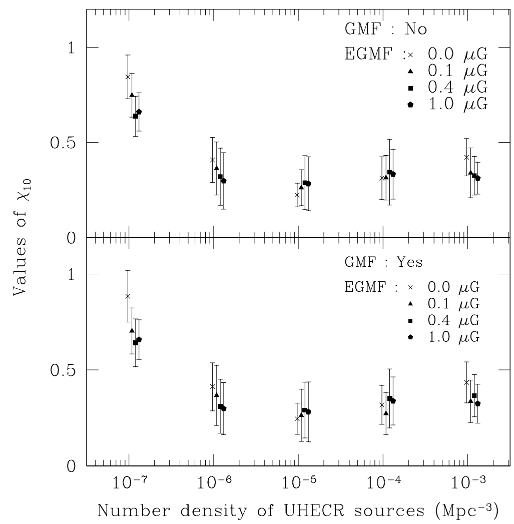

Figure 1: χ_{10}s as a function of the source number density. The error bars originate from 100 times source selection. The GMF is considered in the lower panel while not in the upper panel.

Results

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

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

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

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

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

χ_{10}s are shown in figure 1. While the source number density with 10^{-7} Mpc results in larger value, the others are consistent with each other within 1σ 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 the 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 1σ 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 understand 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 uncertainty of about one order of magnitude. The source density hardly depends on EGMF strength

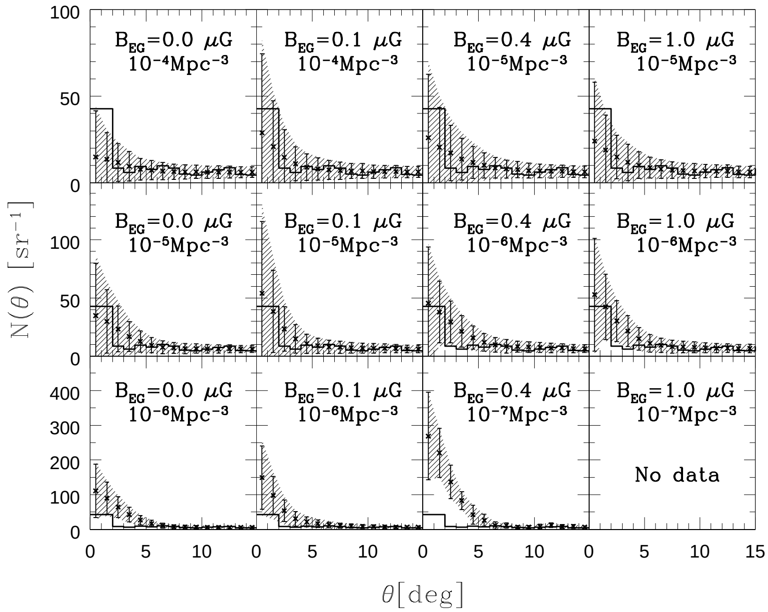

Figure 2: The two-point correlation functions calculated from only source distributions that can predict the LSI. The histograms are the observational result within $4 \times 10^{19} < E < 10^{20}$ eV(49 events). The error bars are from the event selection for finite events and the shaded regions show total 1σ statistical errors. The GMF is included.

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 small number of observed events. Therefore, one of our next interests is how small the uncertainty becomes at Auger era.

In order to investigate this, it is necessary to compare our arrival distribution 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.

Figure. 3 is distributions of χ^2 defined as

$$\chi^2 \equiv \frac{1}{\theta_{\max}} \sum_{\theta=1^\circ}^{\theta=\theta_{\max}} \frac{\left[N_{\rm sim}(\theta) - N_{\rm iso}(\theta)\right]^2}{\sigma_{\rm sim}(\theta)^2 + \sigma_{\rm iso}(\theta)^2}. \quad (3)$$

This value represents the goodness of the fitting. The upper panels show current status corresponding to AGASA result. The distributions with 10^{-4} and 10^{-5} Mpc^{-3} are almost degenerate, so the determination of the number density has large uncertainty. On the left two panels, those with 10^{-5} and 10^{-6} Mpc^{-3} can distinguished. The two source number densities are well distinguishable as we point out above.

200 event observation allows us to discriminate 10^{-5} and 10^{-6} Mpc^{-3} since it can separate the distributions. This event number is 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.

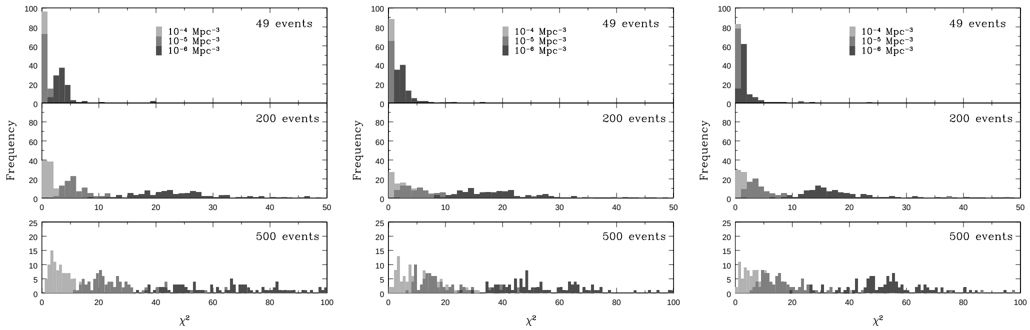

Figure 3: Distributions of χ^2s, calculated from arrival protons above 4×10^{19} eV, at several strengths of the EGMF. The GMF is considered. The strengths of the EGMF are 0.0(*left*), 0.1, (*middle*), and 1.0μG(*right*). The numbers of events are set to be 49 events within $-10^\circ < \delta < 80^\circ$, 200 events and 500 events within the southern hemisphere to emulate Auger.

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 current status (AGASA), the source number density is $\sim 10^{-5}$ Mpc^{-3} with uncertainty of about an order of magnitude due to small number of observed events.

That near future observations increase observed event number can improve that uncertainty. 200 event observation above 4×10^{19} eV can distinguish 10^{-6} Mpc^{-3} from the more source density. This event number is consistent with number observed by Auger until this summer! More event detection enables us to estimate the source number more precisely and, then, to be easy to compare it with that of known powerful objects.

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 current status (49 events). 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 χ^2. Therefore, 10^{-4} and 10^{-5} Mpc^{-3} cannot be distinguished even at 500 event observations.

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