Small Scale Clustering in Isotropic Arrival Distribution of Ultra-High Energy Cosmic Rays

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Abstract

We present numerical simulations on the propagation of ultra-high energy (UHE) protons with energies of $(10^{19.5} - 10^{22})$ eV in extragalactic magnetic fields (EGMF) over 1 Gpc. We use the Optical Redshit Survey (ORS) galaxy sample, which is corrected taking the selection effect and absence of galaxies in the zone of avoidance ($|b| < 20°$) into account. We calculate the cosmic ray spectrum, harmonic amplitude, and two point correlation function, and compare the results of our numerical calculations with the observation. One of our conclusions is that a large fraction of cosmic rays above 10^{20} eV observed by the AGASA experiment might originate in the top-down scenarios, or that the energy spectrum measured by the HiRes experiment might be better. As for the UHECR arrival distribution, we can explain the AGASA observation when $\sim 1/50$ of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ is selected as UHECR sources, and in the case of weak EGMF ($B_{\rm RMS} \leq 1$nG). In terms of the source number density, this constraint corresponds to $\sim 10^{-6}$ Mpc^{-3}.

1. Introduction

The AGASA observation of ultra high energy cosmic rays (UHECRs) above 10^{19} eV reveals at least two features. The cosmic-ray energy spectrum does not show the GZK cutoff [3, 14] because of photopion production with the photons of the cosmic microwave background (CMB) and extends above 10^{20} eV [9]. On the other hand, their arrival distribution seems to be isotropic on a large scale with a statistically significant small scale clustering [10]. In order to reveal their origin, it is important to discuss the observations of cosmic-ray spectrum and the arrival distribution at the same time.

In this study, we perform numerical simulations on the propagation of UHE protons with energies of $(10^{19.5} - 10^{22})$ eV in extragalactic magnetic fields (EGMF) over 1 Gpc. We use the Optical Redshift Survey (ORS) galaxy sample

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[7], which is corrected taking the selection effect and absence of galaxies in the zone of avoidance ($|b| < 20°$) into account, in order to construct realistic source models. We calculate three observable quantities, cosmic ray spectrum, harmonic amplitude, and two point correlation function from our data of numerical simulations. We then compare the results with the AGASA observation [9, 10].

In section 2, we briefly explain our method of calculation. Results are shown in section 3 and their implications are discussed in section 4. We conclude in section 5.

2. Methods

This section provides the method of Monte Carlo simulations for propagating protons in intergalactic space. Detailed explanations are presented in [12].

Particles below $\sim 8 \times 10^{19}$ eV lose their energies mainly by pair creations and above it by photopion production in collisions with photons of the CMB. The pair production can be treated as a continuous loss process considering its small inelasticity ($\sim 10^{-3}$). We adopt the analytical fit functions given by [2]. Since protons lose a large fraction of their energy in the photopion production, its treatment is very important. We use the interaction length and the energy distribution of final protons as a function of initial proton energy which is calculated by simulating the photopion production with the event generator SOPHIA [6].

The EGMF are little known theoretically and observationally. We assume that the magnetic field is represented as the Gaussian random field with zero mean and a Kolmogorov spectrum. In this paper, we show the results for $(B_{\rm RMS}, l_{\rm c}) = (1{\rm nG}, 1{\rm Mpc}), (1{\rm nG}, 10{\rm Mpc}), (10{\rm nG}, 1{\rm Mpc})$, where $B_{\rm RMS}$ and $l_{\rm c}$ are the rms of the strength and the correlation length of EGMF, respectively. Similar method for turbulent magnetic field has been adopted [4, 5, 8, 12, 13].

We assume that the source distribution of UHECRs is proportional to that of the galaxies. We use the realistic data from the ORS galaxy catalog [7], which is nearly full sky survey. The sample is corrected taking the selection effect and absence of galaxies in the zone of avoidance ($|b| < 20°$) into account. Using the data of our numerical simulations and this source model, we calculate the energy spectrum and arrival distribution of UHECRs.

3. Results

In our paper [12], we find that the arrival distribution of UHECRs become to be most isotropic as restricting sources to luminous galaxies ($M_{\rm lim} = -20.5$). This is because luminous galaxies in the Local Super Cluster (LSC) are distributed more widely than faint galaxies, contrary to general clusters of galaxies [11]. However, it is not isotropic enough to be consistent with the AGASA observation,

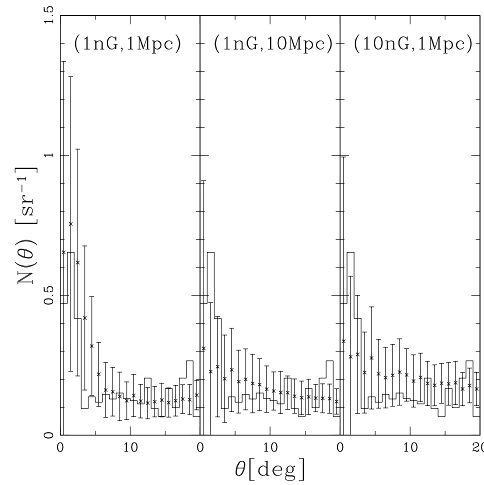

Fig. 1. The two point correlation function predicted by a specific source scenario when $\sim 1/50$ of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ is selected as UHECR sources. The number of simulated events is set to be 57 with energies of $(10^{19.6} - 10^{20.3})$ eV. The histograms represent the AGASA data in this energy range.

even for $M_{\rm lim} = -20.5$. In order to obtain sufficiently isotropic arrival distribution, we randomly select sources, which contribute to the observed cosmic ray flux, from the ORS sample more luminous than -20.5 mag, and investigate dependence of the results on their number. As a result, we find that the isotropic arrival distribution observed by the AGASA can be reproduced when $\sim 1/50$ of the ORS galaxies more luminous than -20.5 mag is selected as UHECR sources. In the following, we present the results predicted by this source location scenario.

In Fig. 1, we show the two point correlation function predicted by a specific source selection for $(B_{\rm RMS}, l_{\rm c}) = (1{\rm nG}, 1{\rm Mpc})$, $(1{\rm nG}, 10{\rm Mpc})$ and $(10{\rm nG}, 1{\rm Mpc})$. Each source distribution is selected so that it predicts the smallest value of χ^2 for respective set of $(B_{\rm RMS}, l_{\rm c})$. The errorbars represent the statistical error due to the finite number of simulated events, which is set to be 57. The correlation of events at small angle scale and sufficient isotropic distribution at larger scale are well reproduced for $(B_{\rm RMS}, l_{\rm c}) = (1{\rm nG}, 1{\rm Mpc})$. There seems to be no significant correlation for another sets of $(B_{rmRMS}, l_{\rm c})$, because of the larger deflection angle of UHECRs. In the cases of strong EGMF or longer correlation length, it appears to be difficult to reproduce the strong anisotropy only at the smallest angle scale, even for the case of minimal value of χ^2.

4. Discussion

As shown in the last section, we find that the small scale anisotropy can not be well reproduced in the case of strong extragalactic magnetic field ($B_{\rm RMS} \geq 10$ nG). Although Isola & Sigl [5] and Sigl, Miniati, & Ensslin [8] conclude that the expected small-scale anisotropy and large-scale isotropy for local enhancement of UHECR sources in the LSC in the presence of the strong EGMF ($\sim 1\mu$ G) are in marginal agreement with the AGASA, the consistency is somewhat worse than that predicted by our scenario for $B_{\rm RMS} = 1$ nG. If local enhancement of UHECR sources in the LSC is disfavored from the observations, there is no way that explains the observed extension of the cosmic-ray spectrum beyond the GZK cutoff. Of cource, we can not draw any firm conclusion about the strength of the EGMF, considering the current limited amount of data.

5. Conclusion

One of our conclusions is that a large fraction of cosmic rays above 10^{20} eV observed by the AGASA experiment might originate in the top-down scenarios, or that the energy spectrum measured by the HiRes experiment [1] might be better. As for the UHECR arrival distribution, we can explain the AGASA observation when $\sim 1/50$ of the ORS galaxies more luminous than $M_{\rm lim} = -20.5$ is selected as UHECR sources, and in the case of weak EGMF ($B_{\rm RMS} = 1$nG).

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