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Propagation of Ultra-High Energy Cosmic Rays above 10^{19} eV in a Structured Extragalactic Magnetic Field and Galactic Magnetic Field

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We perform numerical simulations on propagation of Ultra-High Energy Cosmic Rays (UHECRs) above 10^{19} eV in both a structured Extragalactic Magnetic Field (EGMF) and Galactic Magnetic Field (GMF) and simulate their arrival distribution at the earth. Our structured EGMF model and UHECR source models are constructed out of the IRAS PSCz Catalogue in our method. We follow an inverse process on their propagation from the earth and record the trajectories. This method enables us to save the CPU time efficiently. We construct arrival distribution of UHECRs from these trajectories. By comparing calculated statistical quantities on arrival distribution of UHECRs with the results by the Akeno Ground Air Shower Array (AGASA), we find source number density which reproduce the AGASA data best to be $\sim 5 \times 10^{-6}$ Mpc^{-3}. We also demonstrate arrival distribution of UHECRs with an event number expected by the Pierre Auger Observatory for a few years and examine how the EGMF affects their arrival distribution.

1. Introduction

Nature of Ultra-High Energy Cosmic Rays (UHECRs) is poorly known. One of problems about UHECRs are what is their origin. The two scenarios of their origin are suggested, which are called top-down scenarios and bottom-up scenarios. Bottom-up scenarios assume that some energetic astrophysical phenomena are their origins. UHECRs above 10^{19} eV are thought to be of extragalactic origin since their gyroradii are larger than the thickness of our galaxy. Theoretically, these scenarios have the GZK effect [1, 2] since these source candidates of UHECRs are located at a far distance. UHE protons above $\sim 8 \times 10^{19}$ eV interact the cosmic microwave background (CMB) and lose large fraction ($\sim 20\%$) of their energy by the photopion production. The mean free path of UHE protons through the CMB field is ~ 10 Mpc at 10^{20} eV. Thus the energy spectrum at the earth has a spectral cutoff, which is called the GZK cutoff. However, there are observational discrepancy between the Akeno Ground Air Shower Array (AGASA), which does not observe the GZK cutoff [3], and the High Resolution Fly's Eye (HiRes), which does it [4]. On the other hand, Top-down scenarios assume some processes based on new physics beyond the standard model of the particle physics. Another problem is arrival distribution of UHECRs. The AGASA reported that there is no statistically significant large-scale anisotropy in the observed arrival distribution of UHECRs above 10^{19} eV [5]. Though this fact shows that sources of UHECRs are distributed isotropically, isotropic source distribution cannot explain the small-scale anisotropy reported by the AGASA [5]. The small-scale anisotropy points out astrophysical sources of UHECRs. On the other hand, the HiRes reported that there is no statistically significant small-scale anisotropy [6]. However, this discrepancy about the small-scale anisotropy between the two observations is not statistically significant at present due to small observed events. These problems are expected to be solved by the Pierre Auger Observatory.

In order to obtain information on origin of UHECRs, we need to calculate their arrival distribution using some kinds of source models. Thus we calculate propagation of UHE protons above 10^{19} eV in the intergalactic space, where the Extragalactic Magnetic Field (EGMF) plays an important role, with modifications by the

Galactic Magnetic Field (GMF). We use the IRAS PSCz catalogue [8] in order to construct a structured EGMF model and source model of UHECRs since the EGMF and a distribution of UHECR sources are expected to reflect the structures of the local universe actually observed. Recently, it has been shown that the GMF affects the arrival distribution of UHECRs [10, 11]. We also need to consider modifications on trajectories of UHECRs by the GMF in order to simulate their arrival distribution which is compared with the observational data obtained by the AGASA.

2. A model of the EGMF, the GMF and source of UHECRs

In order to construct a structured EGMF model and UHECR source model reflecting the local structures actually observed around the Milky Way, we use the IRAS PSCz catalogue [8]. This catalogue consists of 14677 galaxies with redshift and infrared fluxes > 0.6 Jy, and covers about 84 % of the sky. We assume the de Sitter universe with $\Omega_m = 0.3, \Omega_\Lambda = 0.7, H_0 = 71\text{km s}^{-1}\ \text{Mpc}^{-3}$ to calculate distance of each galaxy. In order to use this catalogue for construction of a structured EGMF model and UHECR source model, unobserved galaxies due to the selection effect and about 16 % of uncovered region, must be added to the set of the IRAS galaxies. This correction is carried out by using the luminosity function of IRAS PSCz galaxies. See ref.[9] to know detail methods.

We construct a model of the EGMF which reflects the local structures of the universe. Our model of the EGMF is a turbulent magnetic field with the Kolmogrov spectrum and its strength is proportional to total luminosity of galaxies in a cube, with which we cover the universe to be useful for numerical calculations. Each cube is 1 Mpc on a side, which is correlation length of the EGMF. Note that we assume that luminosity of galaxy is proportional to its amount of matter. We set a normalization of its strength to be $\sim 0.4\mu$G in the cube where is in the center of the Virgo cluster. We construct also source model of UHECRs from our sample of galaxies. The number density of UHECR sources is taken as our model parameter. For a given number density, we randomly select galaxies out of our sample with probability proportional to absolute luminosity of each galaxy. We then estimate the source number density which reproduces the observed arrival distribution of UHECRs.

As a model of the GMF, we adopt a bisymmetric spiral field (BSS) model for a spiral field observed and a A0 dipole field for a field in the Galactic halo [10, 11]. We neglect turbulent component of the GMF.

3. Numerical method

We calculate propagation of UHE protons in the intergalactic space. UHE protons are injected with a power law spectrum in the range of $10^{19} - 10^{22}$ eV. This power law spectrum is set to be 2.6 in order to fit the calculated energy spectrum to the one observed by the AGASA [12]. We follow an inverse process of their propagation from the earth, taking into account the three energy loss process, which are the photo-pion production, pair production due to interaction with the CMB and adiabatic energy losses due to the expansion of the universe. All energy loss processes are treated as the continuous processes. Note that energies of UHECRs increase during propagation since we follow an inverse process. UHECRs are injected from the earth isotropically whose charges are taken as -1 and recorded their trajectories. These trajectories can be regarded as trajectories of UHE protons from extragalactic sources. We then select some of them according to a given source distribution (see ref.[9] in detail). The expected arrival distribution can be obtained by mapping the velocity directions of the selected trajectories at the earth. The validity of this method is supported by the Liouville's theorem. This method enables us to calculate only trajectories of UHE protons to reach the earth and to save the CPU time effectively.

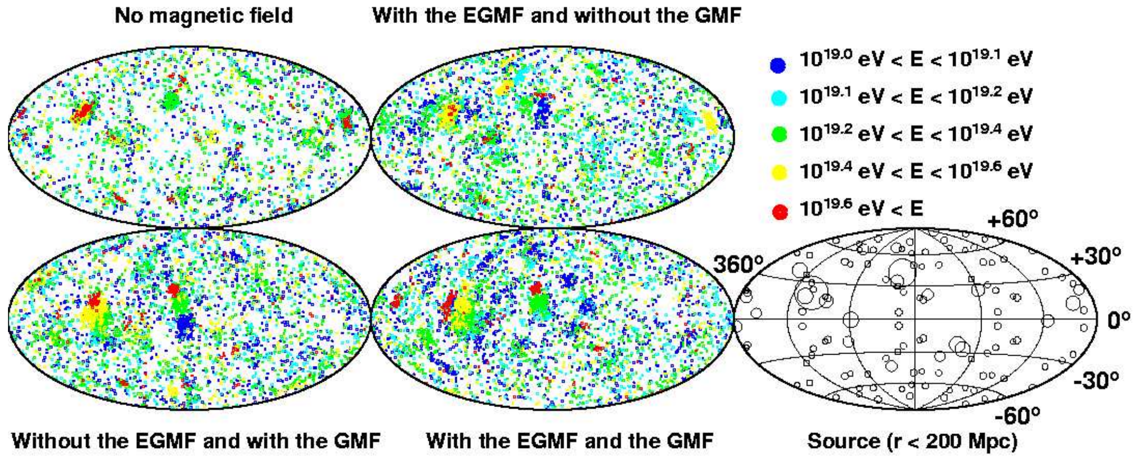

Figure 1. Skymaps of arrival distribution of UHE protons with $E > 10^{19}$ eV at the earth, which is expected for the source model of lower right panel in the galactic coordinate. It is only the sources within 200 Mpc from the earth for clarity as circles of radius inversely proportional to their distance.

4. Conclusions

We simulate arrival distribution of UHECRs and constrain their source number density by comparing their arrival distribution with the observed one by the AGASA. For comparison with the AGASA, we introduce two statistical quantities which reflect their arrival distribution. One is the harmonic amplitudes, which characterize the large-scale anisotropy for the right ascension distribution of events. The other is the two point correlation function, which reflects the small-scale anisotropy of arrival distribution of UHECRs. (See ref.[9] in more detail.) We calculate the harmonic amplitudes and the two point correlation functions of arrival distribution of UHECRs and constrain their source number density by comparing these statistical quantities with those obtained by the AGASA. As a result, $n_{\rm s} \sim 5 \times 10^{-6}{\rm Mpc}^{-3}$ in our source model is the most appropriate number density of UHECR source. This source model can also explain the energy spectrum of the AGASA below 10^{20} eV. This conclusion shows that origins of UHECR above 10^{20} eV differ from our source model, for example top-down scenarios.

We also demonstrate skymaps of arrival distribution of UHECRs above 10^{19} eV in the case $n_{\rm source} \sim 5 \times 10^{-6}{\rm Mpc}^{-3}$. We show one of results of the event generation above 10^{19} eV in figure 1 with a specific source model for $n_{\rm s} \sim 5 \times 10^{-6}{\rm Mpc}^{-3}$. The number of events is 5000, which is the expected number of events observed by the Pierre Auger Observatory for a few years [13]. The skymap generated with both the EGMF and the GMF is in lower middle panel and that without any magnetic fields, that with only the EGMF and that with only the GMF is in the upper left, the upper middle and the lower left panel respectively. This specific source model has three strong (near) sources (see lower right). One is $(l, b) \sim (199°, 34°)$, another is $(l, b) \sim (287°, 19°)$ and the other $(l, b) \sim (25°, 11°)$. Each distance from us is about 77 Mpc, 65 Mpc, and 70 Mpc respectively.

In the absence of any magnetic fields (upper left panel), there are the strong clusterings of events at the directions of these three sources. When the effects of the EGMF are included (upper middle), we find the diffusion of the clustered events. In the lower left panel, the clustered events are arranged in the order of their energies, reflecting the directions of the GMF. This was pointed out by ref.[10] and ref.[11]. Note that we cannot find the clustered events at the direction of one of the strong sources $(l, b) = (25°, 11°)$. This is because UHE protons injected at this source cannot reach the earth due to the GMF. In the lower middle panel, we also find the arrangements at the same point of the lower left panel. But the EGMF diffuses these clustered events as we see in the two upper panels.

In order to see these features quantitatively, we compare the statistical quantities calculated with the EGMF to those calculated without the EGMF in the presence of the GMF. We find that diffusion of arrival distribution of UHECRs due to the EGMF weakens a strong peak at the small angle ($\sim 5°$) of the two point correlation function, which is calculated with only the GMF. This prediction explains the two point correlation function obtained by the AGASA well. In this work, we neglect the turbulent component of the GMF. This component is expected to weaken the two point correlation function at a small angle more and to explain the AGASA data better. This issue are left for one of future investigations. The Auger, which is expected to release some data in this conference, and the EUSO are expected to increase observed events of UHECRs per year drastically. When detailed data of large events of UHECRs are published, we are expected to obtain more detail information on nature of UHECRs.

References

[1] Greisen K. 1966, Phys.Rev.Lett., 16, 748
[2] Zatsepin G.T. & Kuz'min V.A, 1966, JETP Lett., 4, 78
[3] Takeda M. et al., 1998, Phys.Rev.Lett., 81, 1163
[4] Abu-Zayyad T. et al. (The HiRes collaboration) 2004, Phys.Rev.Lett., 92, 151101
[5] Takeda M. et al., 1999, ApJ, 522, 225
[6] Abbasi R.U. et al. (The HiRes collaboration) 2004, ApJ, 612, 900
[7] Yoshiguchi H., Nagataki S. & Sato K. 2004, ApJ, 614, 43
[8] Saunders W. et al. 2000, MNRAS, 317, 55
[9] Takami H., Yoshiguchi H. & Sato K. 2005, arXiv:astro-ph/0506203
[10] Alvarez-Muniz J., Engel R. & Stanev T. 2002, ApJ, 572, 185
[11] Yoshiguchi H., Nagataki S., & Sato K. 2003, ApJ, 596, 1044
[12] Marco D.D., Blasi P. & Olinto A.V. 2003, Astropart.Phys., 20, 53
[13] Capelle K.S., Cronin J.W., Parente G. & Zas E. 1998, Astropart.Phys, 8, 321