A study of the Correlation of Arrival Directions of UHECRs with the Large Scale Structure of the Universe

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Abstract. Ultrahigh energy cosmic rays (UHECRs) are believed to originate from astrophysical sources, which should trace the large scale structure (LSS) of the universe. On the other hand, the magnetic field in the intergalactic space (IGMF), which also traces the LSS of the universe, deflects the trajectories of the charged UHECRs and spoils the positional correlation of the observed UHECR events with their true sources. To explore this problem, we studied a simulation of the propagation of UHE protons through the magnetized LSS of the universe, reported earlier in Das et al. (2008), in which the IGMF was estimated based on a turbulence dynamo model (Ryu et al. 2008). Hypothetical sources were placed inside clusters and groups of galaxies in the simulated universe, while observers were located inside groups of galaxies that have similar properties as the Local Group. We calculated the statistics of the angular distance between the arrival directions of simulated UHE proton events and the positions of candidate sources in our simulation. We compared the statistics from our simulation with those calculated with the Auger data. We discussed the implication of our works on the nature of the sources of UHECRs.

Keywords: ultrahigh energy cosmic rays, large-scale structure of universe, intergalactic magnetic fields

I. Introduction

Recently the Pierre Auger Collaboration reported a significant anisotropy in the arrival directions of ultrahigh energy cosmic rays (UHECRs) [1]. In their study, the nearest neighbor of a given UHECR event is identified among the active galactic nuclei (AGNs) listed in the 12th edition of Veron-Cetty (VC) catalog [2]. The maximum correlation was observed for 20 events out of total 27 events with energy above 57 EeV, when the closest AGN is searched within the angular separation of 3.2° among 442 AGNs with redshift $z \leq 0.018$ (corresponding to the distance $D \leq 75$ Mpc for $h^{-1} = 0.7$). Their study demonstrated a potential association of UHECR events with the sky position of nearby AGNs. However, the statistical significance of this correlation analysis may not yet be robust, since the number of detected events at extremely high energy is still rather small. But at least it implies that the sources of UHECRs might be correlated with the matter distribution in the local universe.

In the correlation analysis, a priori knowledge of the intergalactic magnetic field (IGMF) is essential as it guides the propagation of UHECRs through the intergalactic space. Even with considerable observational efforts, the nature of the IGMF is still poorly known, especially in the low-density regions like filaments, sheets and voids, where activities are relatively weak. In Ryu et al. (2008) [3], we suggested that a part of the gravitational energy is transferred to the magnetic field energy as a result of the turbulent dynamo amplification of weak seed fields in the large scale structure (LSS) of the universe. This model predicts that $\sim 1\%$ of the intergalactic space is magnetized with the field strength $B > 10$ nG, and that the IGMF follows largely the matter distribution in the cosmic web.

Adopting this IGMF model, we estimated that only $\sim 35\%$ of UHE protons above 60 EeV may arrive within 5° of their sources located inside the GZK sphere with radius of 100 Mpc [4]. Considering that the mean deflection angle of super-GZK protons caused by the IGMF in our model is $\sim 15°$ [4], it is natural to expect that, in the correlation study of the Auger UHECR events, a significant fraction of the identified sources within 3.2° may not be the true sources of the UHECRs. In order to explore how the distribution of source candidates and the IGMF in the local universe influence the correlation analysis of UHECRs, we used the simulation results reported earlier in Das et al (2008) [4].

II. Simulation Setup

Following [1], we set the maximum limit of the source-to-observer distance as 75 Mpc. Inside the simulation volume of radius 75 Mpc, $\sim 500$ source candidates (comparable to the number of AGNs from VC catalog) were placed in the highest temperature regions of the cosmic web. Observers were placed in the regions corresponding to groups of galaxies with the halo temperature similar to that of our Local Group. For each UHE proton event above 60 EeV, we computed two angular distances: separation angle and deflection angle. The separation angle, $S$, is the angular distance between the arrival direction of a given event and the position of the nearest AGN among 500 source candidates. The
Fig. 1: Distribution of separation angle ($S$) as functions of distance ($D_S$) of the nearest AGNs in the sky inside a sphere of radius 75 Mpc. Black dots are for the events recorded in our simulation. White circles connected with solid line represent the mean values, $\langle S \rangle$, in the distance bin of $[D_S, D_S + dD_S]$.

The deflection angle, $\theta$, is the angular distance between the arrival direction of a given event and its true source position. Note that the nearest AGN may be not the true source of that event, and $S$ would be on average smaller than $\theta$. Here, we denote $D_S$ as the distance to the nearest AGN with the separation angle $S$, and $D_\theta$ as the distance to the true source with the deflection angle $\theta$.

In our simulated universe, the intergalactic space was magnetized by turbulent plasma motions generated during the structure formation [3]. For simplicity, the injection proton spectrum at source locations was characterized by a power low in the energy range above $6 \times 10^{19}$ eV with the exponent of $\gamma = 2.7$.

III. RESULTS

A. Separation Angle and Deflection Angle

In Figure 1, we show the distribution of separation angle ($S$) versus the distance of the nearest source ($D_S$). Each dot denotes a recorded event obtained from simulation. The white circles connected with solid line represent the mean values of $S$ for the events from AGNs with the distance bin of $[D_S, D_S + dD_S]$. We note that the mean separation angle $\langle S \rangle$ shows a U-shape distribution (see the discussion below). Overall $\langle S \rangle$ is smaller than $\sim 4^\circ$ for all $D_S$, and does not change sensitively with $D_S$. The mean separation angle over all the simulated events is $\langle S \rangle_{\text{sim}} = 3.6^\circ$.

In Figure 2, we compare the results of our simulation with the Auger data [5]. Asterisks denote the highest energy 27 Auger events that are correlated with the position of nearby AGNs listed in VC catalog. The mean separation angles for the 20 events that gives the maximum correlation, for the 26 events that excludes the event with $S > 27^\circ$ and for all the 27 events are $\langle S \rangle_{\text{Auger}} = 1.91^\circ$, $3.23^\circ$, and $4.13^\circ$, respectively. The filled circles connected with dotted line represent the mean values of $S$ (same as those in Figure 1), while the filled circles connected with solid line refer to the median values of $S$ for the simulated events. For a given distance bin, $[D_S, D_S + dD_S]$, the solid vertical lines with marks on the both sides of the median values (the first and third quartiles) provide the measure of dispersion on $S$. Note that 15 out of 27 Auger events lie within the quartile marks obtained from our simulation data.

Figure 3 shows the distribution of the deflection angle ($\theta$) of UHE proton events with true sources at distance $D_\theta$. Again each dot represents a simulated event. The white circles connected with dotted and solid lines are for the mean and the median values of $\theta$, and the solid vertical lines with marks denote the spread of $\theta$ in the distance bin $[D_\theta, D_\theta + dD_\theta]$. The distribution of $\theta$ shows a bi-modal pattern divided around an intermediate distance at $D_\theta \sim 20$ Mpc [4]. The events with small $D_\theta$ are likely to be the cases in which both the source and observer belong to the same filament. These particles are more likely to travel through strongly magnetized filaments rather than void regions, resulting in large
deflection angles. On the other hands, for the events with large \(D_\theta\), the particles come from distant sources associated with different filaments. Some of UHECRs may fly through voids and arrive with small \(D_\theta\), while most are deflected significantly by the IGMF. The U-shape distribution of \(\langle \theta \rangle\) with minimum at \(D_\theta \sim 20\) Mpc, as well as the U-shape distribution of \(\langle S \rangle\) in Figure 1, are the consequence of the bi-modal pattern, and a clear signature of the magnetized LSS of the universe.

The mean deflection angle of all the simulated events is \(\langle \theta \rangle_{\text{sim}} = 14^\circ\), which is \(\sim 3\) times larger than \(\langle S \rangle_{\text{sim}}\). One might wonder if deflection angles of this magnitude could erase the anisotropy in the arrival directions of UHECRs, which is observed in the Auger data. However, the large deflection angle does not necessarily lead to the general isotropy of UHECR arrival directions, since the IGMF distribution is also correlated with the LSS. Suppose UHECRs are ejected from sources inside the Local Supercluster. Some of them will fly along the Supergalactic plane and arrive at Earth with relatively small \(\theta\). Some of them may be deflected into void regions, but they may not get reflected back to the direction toward us due to lack of the turbulent IGMF there. In this scenario, the irregularities in the IGMF serve as the ‘scatters’ of UHECRs. So we will observe fewer UHECRs from void regions where both sources and scatters are underpopulated. Consequently, the anisotropic behavior in arrival directions could be maintained even for the large values of \(\langle \theta \rangle\), substantially larger than that of \(\langle S \rangle\), if both source locations and the IGMF distribution are anisotropic in the local universe.

In order to test the validity of our models for the distributions of the IGMF and nearby AGNs, we compare the distribution of \(S\) obtained from our simulation with that of the Auger data. In Figure 4 we show the cumulative fraction of events, \(F(\leq \log S)\), for the Auger data (open circles) and the simulation data (solid line). The Kolmogorov-Smirnov (K-S) test yields the maximum difference of \(D = 0.17\) between the two distributions, so the significance level of \(P \sim 0.37\). It means that we cannot reject the null hypothesis that the two distributions are statistically identical.

### B. Probability of Finding UHE Proton Sources

Since the deflection angle caused by the IGMF is larger than the mean angular separation, that is, \(\langle \theta \rangle > \langle S \rangle\), there is a good chance that for a given UHECR event, the closest source in the sky may not be its true source. To explore the implication, we calculate the fraction of true identification, \(f\), as the ratio of the number of events for which nearest objects are in fact true sources to the total number of simulated events. This is a measure of the probability to find the true sources of UHE protons in our model, when the nearest candidates are chosen blindly (which is the best we can do with observed data). In Figure 5, we show the fraction as function of separation angle, \(S\). For \(S \sim 2^\circ\), the fraction is \(\sim 50\) %. As separation angle increases, the fraction decreases gradually to \(\sim 10\) %, indicating lower probability to find the true sources at larger separation angles. On average, in only 1 out of \(\sim 3\) cases, the true
Fig. 5: Fraction ($f$) of recorded UHE proton events for which their true sources are identified as the closest AGNs in the sky, as a function of separation angle ($S$).

sources of UHE protons can be identified, if we assume that our model for the IGMF is valid.

IV. Summary

In the search for the sources of UHECRs, understanding the propagation of charged particles through the magnetized LSS of the universe is important, if UHECRs originate from extragalactic sources. At present, the details of the IGMF is still uncertain, mainly due to the limited available information from observation. In this contribution, we adopted a realistic model universe that was described by a cosmological structure formation simulation [3]. Our simulated universe represents a characteristic volume of the cosmic web, in which the distribution of the IGMF was calculated by a physical model based on turbulent dynamo. Hypothetical sources of UHE protons were placed at the deepest gravitational potential wells along the LSS, and observers were placed at groups of galaxies like our Local Group.

We then followed the propagation of UHE protons above 60 EeV ejected from the hypothetical sources within a sphere of radius 75 Mpc with observers at the center, in the simulated model universe [4]. We calculated two angular distances for a given UHE proton event: the separation angle $S$ from its nearest source candidate and the deflection angle $\theta$ from it true source. The distribution of $S$ depends on the relative sky distributions of UHECR events and source candidates. We find the mean value of $S$ for simulated events is $\langle S \rangle_{\text{sim}} \approx 3.6^\circ$, while $\langle S \rangle_{\text{Auger}} \approx 4.13^\circ$ for the 27 Auger events ($\langle S \rangle_{\text{Auger}} \approx 3.2^\circ$, if the event with $S > 27^\circ$ is excluded). On the other hand, the distribution of $\theta$ is greatly affected by the IGMF in the LSS. The mean value is $\langle \theta \rangle_{\text{sim}} \approx 3\langle S \rangle_{\text{sim}} \approx 14^\circ$ for the simulated events. (For the 27 Auger events, of course, there is no way to estimate the true deflection angles.)

We tested whether the distributions of separation angle, $S$, for simulated events and the 27 Auger events are identical. The significance level that the two distributions are drawn from the identical population is $P \approx 0.37$, according the Kolmogorov-Smirnov test. Thus, we argue that our simulation results are in a fair agreement with the Auger data.

We point that, although the mean deflection angle $\langle \theta \rangle_{\text{sim}}$ is large, the arrival directions of UHECRs would still carry the anisotropy signature of our local universe, since the IGMF is also correlated with the matter distribution in the LSS.

The fact that $\langle \theta \rangle_{\text{sim}} > \langle S \rangle_{\text{sim}}$ implies that some of the identified source candidates may not be the true sources, if we assume that our model of the IGMF is correct. We estimate the probability of true identification as the ratio of the number of true source identification to the total number of simulated events. This probability is $\sim 50\%$ at $S \sim 2^\circ$, but only $20 - 30\%$ for $S = 3^\circ - 4^\circ$ and decreases to $\sim 10\%$ at larger separation angle. This suggests that identifying the sources of UHECRs from positional correlation analysis may not be straightforward.

Finally, we note that $\langle S \rangle$ and $\langle \theta \rangle$ show U-shape distributions, resulting from the bimodal pattern in which $\theta$ is on average larger for either nearby sources ($D_\theta < \sim 10$ Mpc) or distant sources ($D_\theta > \sim 30$ Mpc) with its minimum at the intermediate distance, $D_\theta \sim 20$ Mpc. This is a characteristic imprint of the structured IGMF to the deflection angle distribution. We suggest that the imprint can be tested with the distribution of $S$, when enough observed UHECR events are accumulated.

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