Possibility to Constrain the Galactic Magnetic Field by the Highest Energy Cosmic Rays

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***Abstract*. We investigate the cross-correlation between cosmic ray protons above $\sim 6 \times 10^{19}$ eV, whose trajectories have been modified by Galactic Magnetic Field (GMF), and their sources in the local Universe by simulations using 4 plausible GMF models. Significant correlation appears at a few degree without being spoiled by GMF except in the case of the northern sky with axisymmetric spiral GMFs. Thus, if we find a lack of correlation in the northern sky, it might support the axisymmetric structure of GMFs. On the other hand, cross-correlation signals predicted from the 4 GMF models cannot be distinguished with sufficient significance because of the large uncertainty of source positions. In order to constrain GMF locally, it is effective to focus on cosmic rays from a nearby source. We demonstrated the arrival directions of protons emitted from local sources and showed that the arrangement of arriving cosmic rays emitted from a source, whose spatial pattern depends on the structure of local GMF, is a plausible way to obtain information on GMF.**

***Keywords*: highest energy cosmic rays, Galactic magnetic field, propagation**

I. Introduction

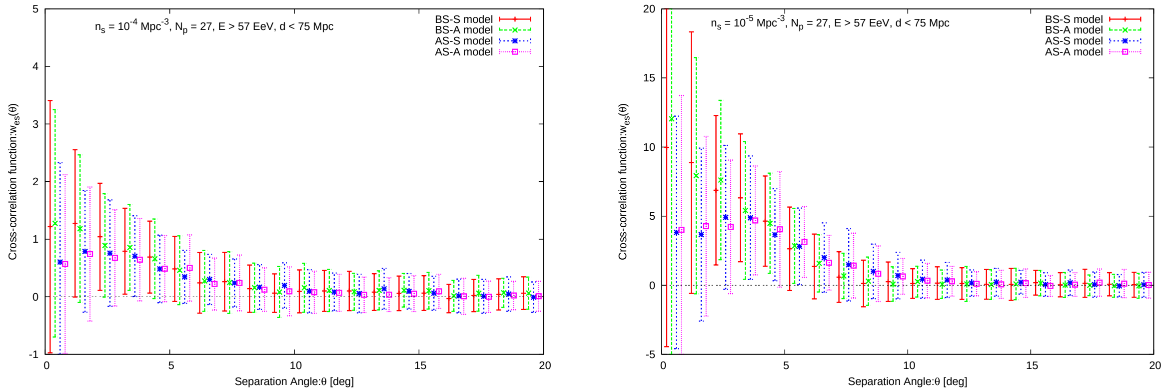
Recently, we have been able to approach the origin of the highest energy cosmic rays (HECRs) by developing HECR observatories, especially Pierre Auger Observatory (PAO), though specific sources of HECRs are still unknown. The positional correlation between HECRs above $\sim 6 \times 10^{19}$ eV and nearby astrophysical objects reported by the PAO [1] was an important step to investigating HECR sources in the sense that the PAO showed not only HECR sources are extragalactic objects but also intervening (intergalactic and Galactic) magnetic fields are not as strong as they delete information on the positions of HECR sources. Although the PAO reported objects which correlates with the PAO data within $\sim 3^\circ$, it is still problematic whether they are real HECR sources because almost all of them have weak activity [2]. In order to identify HECR sources, importance to kindly estimate the effect of intervening magnetic fields to the arrival directions of HECRs increases.

All HECRs observed at the Earth have been inevitably affected by Galactic magnetic field (GMF). The deflection of trajectories of HECRs by GMF have been discussed in many works [3], [4], [5]. In this study, we investigate the cross-correlation between the highest energy protons and their sources in the local Universe by simulations taking their propagation in GMF into account. We also investigate the possibility to distinguish several GMF models by using the same simulations. Only protons are considered in this study.

II. Calculation and Analytical Method

In order to simulate the arrival distribution of extragalactic protons, we adopt an method developed in our previous work [6]. This method enables us to calculate their arrival distribution taking into account their propagation in magnetized space for a given source distribution. In this method, we focus on inversely propagating protons ejected from the Earth. Thus, protons arriving at the Earth are treated as protons with the charge of -1 (like *anti-protons*) ejected from the Earth, and all energy-loss processes of protons, which are photopion production, pair creation with cosmic microwave background, and adiabatic energy-loss, are treated as energy-*gain* processes in a continuous energy-changed approximation. We also consider the apertures of the PAO and Telescope Array following Ref. [7] and uncertainty in the determination of the arrival directions of primary HECRs in the simulations. The former is analytically estimated by $a_0 = -35.2^\circ$ (39.3°), the terrestrial latitude of the detectors, and $\theta_{\rm cut} = 60^\circ$ (45°), a zenith angle for an experimental cut, for the PAO (TA). The latter is assumed to be 1°.

In this study, only GMF is taken into account. Intergalactic magnetic field is neglected for simplicity. We adopt 4 GMF models proposed in Ref. [3]. The GMF models are characterized by 2 features: field reversals between the Galactic arms, and parity above and below the Galactic plane. All the GMF models have a spiral structure either with (bisymmetric:BS) or without (axisymmetric:AS) the field reversals. About the parity, the direction of the spiral fields is opposite (A-type) or the same (S-type) above and below the Galactic plane. There are observational evidences to support several models, but the evidences does not converge into one model at present because there are uncertainties to originate from small scale irregularities in GMF and the theoretical



(a) $n_s \sim 10^{-4}\text{Mpc}^{-3}$ (b) $n_s \sim 10^{-5}\text{Mpc}^{-3}$

Fig. 1. Cross-correlation functions between the arrival directions of protons above 5.7×10^{19} eV simulated in the cases of the 4 GMF models and the positions of their sources within 75 Mpc. The number of protons corresponds to a PAO result [1]. The aperture of the PAO is assumed.

modelling. Thus, we consider all the combinations of the type of field reversals and parity as models of GMF. Although the random component of GMF whose strength is 0.5-2 times as large as the spiral component [8], it can be neglected because it subdominantly affects HECR propagation due to its coherent length much smaller than the larmor radius of the particles considered in this study.

We also adopt a source model which is related to galaxy distribution used in Ref. [9], which was originally proposed in Ref. [6]. In this model, we regard a set of galaxies randomly sampled from a processed IRAS catalog as a source distribution, which is a galaxy set in which selection effects of the IRAS PSCz catalog [10] are modified. Therefore, the source distribution still keeps information on large-scale structure of the Universe. It is assumed that all sources emit protons steadily with the same power and a power-law spectrum with the index of -2.6. In this study, we set the number density of HECR sources to $n_s \sim 10^{-4}$ Mpc^{-3} and $\sim 10^{-5}$ Mpc^{-3} which can well reproduce the anisotropy in HECR arrival distribution observed by the PAO [11]. Since sources are randomly selected, the positions of sources have uncertainty. Thus, we consider 100 source distribution for each n_s and discuss the cross-correlation statistically.

In order to estimate the correlation between the arrival directions of HECRs and their sources, a cross-correlation function adopted in Ref. [9] is used:

$$w_{\rm es}(\theta) = \frac{ES(\theta) - E'S(\theta) - ES'(\theta) + E'S'(\theta)}{E'S'(\theta)}. \quad (1)$$

Here, E, S, E' and S' represent simulated protons, sources in simulation, protons randomly distributed following the apertures of HECR observatories and randomly distributed sources. $ES(\theta)$ is a normalized pair-count between HECR events and sources with the separation angle of θ, and the others are similarly defined. E' and S' correct the effect of anisotropic apertures of HECR and their source observatories.

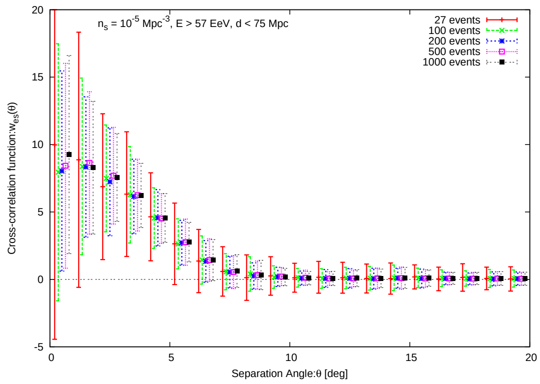
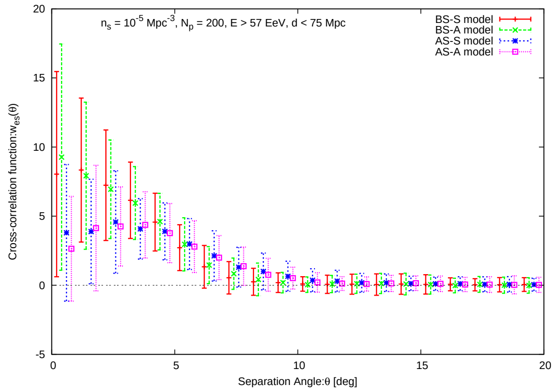


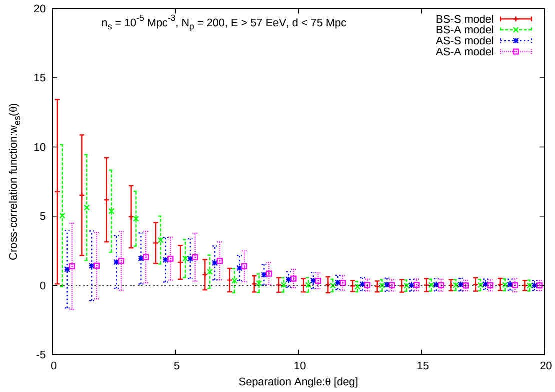
Fig. 2. Cross-correlation functions predicted in the BS-S GMF model. The numbers of protons are 27, 100, 200, 500 and 1000. $n_s \sim 10^{-5}$ Mpc^{-3} is assumed. Large error bars which originate from the random sampling of sources are left even if the number of events increases.

III. RESULTS

First of all, we review the deflections of the highest energy protons by the 4 GMF models according to the results of Ref. [5]. An important thing is that not only protons with arrival directions near the Galactic Plane (GP) but also protons arriving far from the GP could be affected by GMF because even the latter protons inevitably propagate near the GP to reach the Earth. Thus, the spatial distribution of their deflection angles is complicated. The spatial distribution is strongly dependent on the type of the field reversals of GMF. In the BS models, the field reversals affect the trajectories of propagating protons so as to decrease their deflection angles once the protons pass through the field reversals. On the other hand, such effect does not occur in the AS models because of the lack of the field reversals. Therefore, the BS models generally predict smaller deflection angles of protons than the AS models. The difference appears, specially in the northern sky, which includes the Galactic anti-center. Thus, the northern sky is expected to be a better site to observe the difference by the different GMF structures. The parity of GMF



(a) Assuming the aperture of the PAO



(b) Assuming the aperture of the TA

Fig. 3. Cross-correlation functions between 200 simulated protons and their source distribution within 75 Mpc. $n_s \sim 10^{-5}$Mpc^{-3} is assumed.

little change their deflection angles, though it varies their arrival directions.

We start with simulating a current situation (before this ICRC) of the PAO. Fig. 1 shows the cross-correlation functions between the arrival directions of 27 protons above 5.7×10^{19} eV simulated in the cases of the 4 GMF models and their sources within 75 Mpc. The number densities of HECR sources are set to $n_s \sim 10^{-4}$ Mpc^{-3} (*left*) and 10^{-5} Mpc^{-3} (*right*), respectively. The aperture of the PAO is assumed. The dots and error bars are the averages and standard deviations of the cross-correlation functions estimated by 100 realizations. These values are estimated as we realize 100 source distributions by repeating the sampling of sources randomly and then realize the arrival distribution of protons 1 time for every source distribution. Thus, the error bars include not only errors due to the finite number of events but also those originating from the sampling of sources.

The right panel shows the larger values of cross-correlation than the left panel because it is easy to count cross-correlation with sources which are not real HECR sources if the number of sources is large. Reflecting this, cross-correlations for $n_s \sim 10^{-4}$ Mpc^{-3} predicted by all the 4 GMF models are consistent with a lack of correlation. Thus, cross-correlation of HECRs with their sources is not always found at present. Hence, specific active galactic nuclei which correlates with the PAO events are not always real HECR sources if real HECR sources have physical features assumed here. However, this situation can be easily improved by increasing number of events.

For $n_s \sim 10^{-5}$Mpc^{-3}, positive correlation is found at 2°-4° in the BS models even when the number of events is only 27. This scale corresponds to the angular scale of correlation found by the PAO. On the other hand, predictions in the AS models are almost consistent with no correlation.

From both the panels, we can find that the cross-correlations calculated from the 2 BS models are behaved similarly, and also in the case of the AS models. This fact indicates that this cross-correlation analysis cannot distinguish between BS models and between AS models, reflecting the deflection angles of protons is almost unchanged between S-type and A-type parity. Note that their deflection directions could be varied.

The error bars can be reduced by increasing the number of observed HECRs because these include errors originating from the finite number of HECRs. Fig. 2 shows the cross-correlation functions of several numbers of simulated protons in the case of the BS-S model, in which the aperture of the PAO is taken into account. As increasing the number of events, the error bars become small, but are saturated at more than 200 events. This also happens if we assume the other GMF models, $n_s \sim 10^{-4}$ Mpc^{-3}, and the aperture of the TA.

Next, we discuss the same discussions by using 200 protons because the error bars are sufficiently saturated by ~ 200 protons detection. The left panel of Fig. 3 is the same as the right panel of Fig. 1 (for $n_s \sim 10^{-5}$ Mpc^{-3}), but the number of protons is 200. The right panel is similar to the left, but the aperture of the TA is taken into account.

For the southern sky (*left*), all the GMF models lead to inconsistency with a lack of correlation at a small angular scale. The angular scales of the inconsistency are at around $\sim 5°$, but a little different between the BS and AS models, which reflects the fact that the deflection angles in the AS models are generally larger than in the BS models. However, this is quantitative because the cross-correlations are not distinguishable within the error bars. These situations also happen for $n_s \sim 10^{-4}$ Mpc^{-3}. Thus, the PAO is expected to find correlation with real sources within 5° in any cases.

On the other hand, for the northern sky (*left*), predictions of the AS models are almost consistent with no correlation, though the BS models predict significant correlation within $\sim 5°$. A lack of correlation in the AS models results from the large deflection angles of protons in the direction of the Galactic anti-center. These situations also happen for $n_s \sim 10^{-4}$ Mpc^{-3}. Thus, if HECR observatories in the northern sky does not find the sources after the detection of 200 protons above

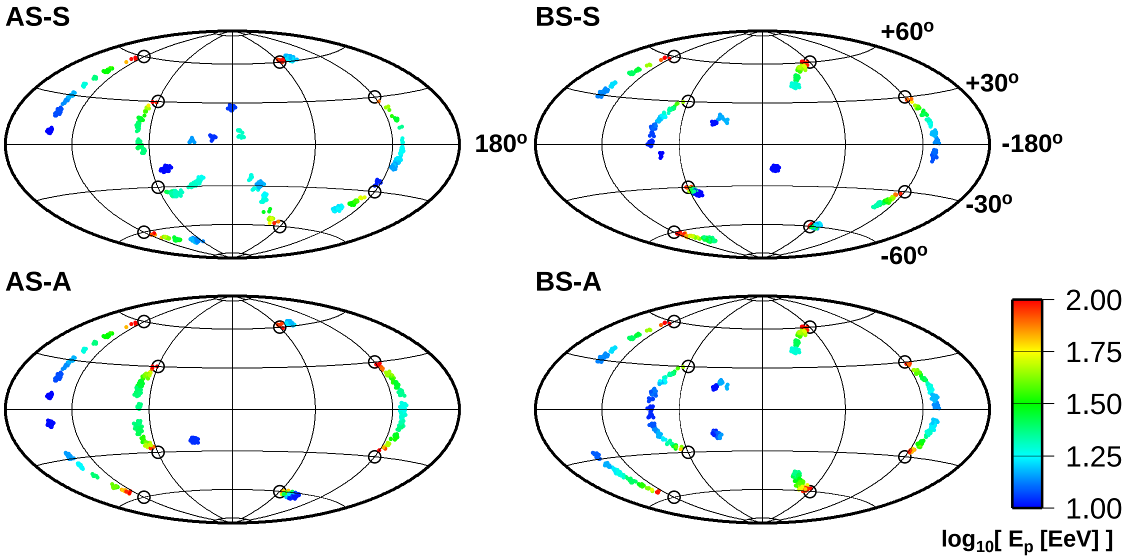


Fig. 4. Arrival directions of protons above 10^{19} eV emitted from specific sources with the distances of 30 Mpc. The positions of sources are represented as bold circles. Protons emitted from a source are regularly arranged in the order of their energy, which depends on their arrival directions and the structures of GMF.

$\sim 6 \times 10^{19}$ eV and real HECR sources have features assumed in this study, it implies that the AS-like GMF might be realized.

Next, we focus on cosmic ray protons from several nearby sources and their arrival distribution. Since the deflection directions of the protons depend on the positions of the sources and structures of GMF, this approach is expected to obtain information on local GMF. Fig. 4 shows the arrival directions of protons above 10^{19} eV emitted from several specific sources with the distances of 30 Mpc. The positions of the sources are represented as bold circles, and arriving protons and their energy are shown in dot and color, respectively.

Protons emitted from a source are regularly arranged in the order of their energy, reflecting the local structures of GMF because the GMF models have large-scale regular (spiral) fields. In the GMF models with the A-type parity, the deflection directions of protons are symmetric against the GP, reflecting anti-parallel spiral fields above and below the GP. Since there are regions where the deflection angles of protons are so small, it is possible to find a point-like signal. Arriving cosmic rays passing near the Galactic Center are strongly scattered by strong GMF and then information on their sources is lost. Some points not associated with the sources are such protons.

Such arrangement structures of HECRs can imply the local structure of GMF by their pattern. However, in a real situation, HECRs from many other sources are worked as a background to these structures as HECR observatories have reported, in fact, isotropy of HECR distribution at around 10^{19} eV. Thus, we need to focus on a high energy part of arriving protons, in which the anisotropy has been reported, to find the arrangement structures. Also, it depends on the positions of a few nearest sources in the Universe whether GMF structure is constrained by this method.

Finally, we should notice that all discussions in this study are based on the assumption of static generation of HECRs. If we assume transient generation of HECRs, the cross-correlation signals may be changed and the arrangement of protons from a nearby source in the order of their energy is strongly weaken because of the time-delay of HECRs during propagation in the Galactic space.

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