DISTORTION OF ULTRA-HIGH-ENERGY SKY BY GALACTIC MAGNETIC FIELD

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ABSTRACT

We investigate the deflections of UHE protons by Galactic magnetic field (GMF) using four conventional GMF models in order to discuss the positional correlation between the arrival distribution of UHECRs and their sources. UHE protons coming from the direction around the Galactic center are highly deflected above 8° by the dipole magnetic field during their propagation in Galactic space. However, in bisymmetric spiral field models, there are directions in which the deflection angle is below 1°. One of these directions is toward Centaurus A, the nearest radio-loud active galactic nucleus that is a possible UHECR source candidate. On the other hand, UHE protons arriving from the direction of the Galactic anticenter are generally less deflected, especially in bisymmetric spiral field models. Thus, the Northern Hemisphere, not including the Galactic center, is suitable for studies of correlation with sources. The dependence on model parameters is also investigated. The deflection angles of UHE protons are dependent on the pitch angle of the spiral field. We also investigate distortion of the supersegalactic plane by the GMF. Since the distortion in the direction around the Galactic center strongly depends on the GMF model, we can obtain information on the GMF around the Galactic center if Pierre Auger Observatory finds significant positional correlation around the supersegalactic plane.

Subject headings: cosmic rays — Galaxy: general — magnetic fields — methods: numerical

Online material: color figures

1. INTRODUCTION

The origin of ultra-high-energy cosmic rays (UHECRs) is one of the most intriguing problems in astroparticle physics. In order to reveal their nature and sources, UHECR observatories with larger exposures have been constructed. Now, the total exposure of Pierre Auger Observatory (PAO) already exceeds that of High Resolution Fly’s Eye (HiRes), which had been the largest detector before the PAO era (Pierre Auger Collaboration 2007). Expectations for elucidating of UHECR sources have been raised since PAO can detect more than 100 events per year above $4 \times 10^{19}$ eV, which is an energy threshold where the Akeno Giant Air Shower Array (AGASA), which is the largest air shower array, found small-scale anisotropy of observed UHECR arrival distribution from its 57 events (Takeda et al. 1999).

The discussions toward UHECR astronomy have recently begun. There seem to be two standpoints for UHECR astronomy. One is the study of direct correlation between UHECR sources and observed UHECR arrival directions. This can be expected if the Galactic magnetic field (GMF) and extragalactic magnetic field (EGMF) are weak enough to deflect UHECR trajectories weakly. However, the nature of the GMF and EGMF are poorly known observationally and theoretically. Recently, several simulations of large-scale structure formation with magnetic field have described local magnetic structures (Sigl et al. 2003; Dolag et al. 2005). Sigl et al. (2003) claimed that UHECR astronomy may not be possible if their source distribution model, magnetic structure, and observer position are confirmed by future observation, since even UHE protons with $10^{20}$ eV are deflected by 20° or more by the structured EGMF. On the other hand, Dolag et al. (2005) showed that most of the highest energy cosmic rays are very weakly deflected by the EGMF, since strong magnetic field ($\sim \mu G$) is highly localized at clusters of galaxies. Therefore, the deflection angles of UHECRs are controversial. The understanding of the GMF is better than that of the EGMF, but also poor, as briefly reviewed in § 2. Recently, PAO has reported the positional correlation between the arrival directions of the highest energy events and nearby active galactic nuclei (AGNs; Pierre Auger Collaboration 2007). AGASA also reported small-scale anisotropy of the UHECR arrival distribution within its angular resolution (Takeda et al. 1999). These results are one piece of corroborating evidence for this approach. For the study of direct positional correlation, the number density of UHECR sources also holds a crucial role. If the source number density is larger, the number of observed events to unveil UHECR sources or source distribution is larger. The UHECR source number density is constrained at $\sim 10^{-7}$ Mpc$^{-3}$ using small-scale anisotropy observed by AGASA (Blasi & de Marco 2004; Kachelriess & Semikoz 2005; Takami & Sato 2007), but this constraint also has large uncertainty due to the small number of observed events. However, this uncertainty will be reduced well by near future observation (Takami & Sato 2007). In any case, these uncertainties prevent our understanding of UHECR sources based on the positional correlation at present.

The other standpoint is a purely statistical approach. Medium-scale ($\sim 20°$) anisotropy was found in the arrival distribution of the highest energy cosmic rays in data combined with results of several observatories before the PAO era (Kachelriess & Semikoz 2006). This angular scale corresponds to a typical scale of event clusterings. The cumulative two-point autocorrelation function of the observed events can reproduce well that of mock data calculated by Monte Carlo simulation assuming that the UHECR source distribution traces nearby large-scale structure within $z \approx 0.02$, but there is no statistically significant cross-correlation between the observed events and the structure (Cuoco et al. 2008b). They claimed that the medium-scale anisotropy reflects the local large-scale structure as UHECR sources. Cuoco et al. (2008a) suggested that such a statistical method is a powerful tool to reveal UHECR source distribution even if the GMF is considered.

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This medium-scale anisotropy was also found in PAO data (Møllerach et al. 2007).

Our recent studies have been based on the former standpoint. In our previous study (Takami & Sato 2008), we discussed the possibility that future observations of UHECR arrival distributions can unveil the large-scale structure of the UHECR source distribution. We calculated the positional correlation between the simulated arrival distribution of UHE protons and their source distribution that reproduces the local structures, taking into account their propagation in a structured EGMF with plausible strengths. Our EGMF model was also constructed under simple assumptions so that it reproduces the observed local structures. Taking into account uncertainties in the EGMF strength and the source number density, we investigated the positional correlation in several parameters. Our studies using source distribution and EGMF models based on astronomical observations just predicted the recent PAO parameters. Our studies have been based on the former standpoint. In our previous study (Takami & Sato 2008), we discussed the EGMF as a first step toward the direct positional correlation study between UHECR arrival directions and source positions. The GMF was neglected. However, the GMF affects the arrival directions of UHECRs (Alvarez-Muñiz et al. 2002; Takami et al. 2006; Kachelriess et al. 2007). Thus, as a next step, it is necessary to discuss the deflections of UHECRs by the GMF.

In this study, we calculate trajectories of UHE protons in Galactic space and investigate their deflections by the GMF. We adopt the backtracking method for calculating the trajectories. Trajectories of particles with proton mass and charge of $-1$ injected from the Earth can be regarded as those of extragalactic protons. We focus on UHE protons above $10^{19.8}$ eV, which is the best indicator of positions of UHECR sources. We also investigate the distortion of the extragalactic sky by the GMF and discuss its effect on correlation studies.

The composition of UHECRs is essential for positional correlation studies. Heavier components of UHECRs are more strongly deflected by magnetic fields and disturb the positional correlation. One of the observables for the composition is the depth of shower maximum, $X_{\text{max}}$, which can be measured by fluorescence detectors. Its average value, $\langle X_{\text{max}} \rangle$, is sensitive to the UHECR composition. High Resolution Fly’s Eye reported that compositions of cosmic rays above $10^{19}$ eV are dominated by protons as a result of $\langle X_{\text{max}} \rangle$ measurement (Abbasi et al. 2005). Recent results by PAO are compatible with the HiRes results within systematic uncertainty (Unger et al. 2007). Another observable is the muon density in the extensive air shower of UHECR, observed by ground arrays. Recent studies of the muon content indicate some fraction of heavier components in the highest energy cosmic rays (Engel et al. 2007; Glushkov et al. 2007). However, the interpretation of these two observables is dependent on hadronic interaction models, which include uncertainties in the UHE energy region. On the other hand, the correlation with AGNs found by PAO indicates a light composition. For the positional correlation study, the proton component is a powerful tool. Thus, despite such uncertainties in UHECR compositions, we consider only protons in this study.

This paper is organized as follows: in § 2 we explain four GMF models used in this study. In § 3, we investigate the deflection of UHE protons with $10^{19.8}$ eV in the GMF models introduced in § 2. Dependence on parameters of the GMF models is discussed in § 4. In § 5, we summarize results of deflection and discuss its effects on correlation studies.

### 2. GALACTIC MAGNETIC FIELD

In this section, we briefly summarize current knowledge of the GMF and explain GMF models used in this study. For more details, see review articles (Valleé 2004; Han 2007).

Faraday rotation measures of Galactic pulsars and extragalactic radio sources indicate that the GMF has two components: a large-scale regular field of strength a few microgauss and a turbulent or random field of comparable strength. The regular component includes the disk and halo components.

The regular component in the Galactic disk has a pattern resembling that of the matter in the Galaxy. This spiral component could be well described by the axisymmetric (AS) or bisymmetric (BS) field model. The BS model has several field reversals, while the AS model does not. The halo field can be classified by parity at disk crossing. The odd parity, A (even parity, S), represents the situation in which the spiral components in the halo fields above and below the Galactic plane are antiparallel (parallel). From combinations of the disk field models and the halo field models, four models are proposed. Many works have discussed which models are favored. Valleé (2005) reported that a concentric ring model (like an AS model) with a single field reversal and S-type parity are preferred (AS-S model). On the other hand, Han et al. (2006) proposed that the spiral component has a bisymmetric structure with reversals on the boundaries of the spiral arms. In the halo field, Han et al. (1997, 1999) suggested that the A-type parity is preferable. This corresponds to a BS-A model. Both reports are based on observational results. However, discrimination between the models is complicated by the presence of smaller scale irregularities in the magnetic field, as well as uncertainties in the theoretical modeling. Thus, we adopt all four combinations and investigate the deflections of UHE protons in the Galactic space.

In the models, the radial and azimuthal components are given by

$$B_r = B(r, \theta) \sin \psi, \quad B_\theta = B(r, \theta) \cos \psi.$$  \hspace{1cm} (1)

The $r$, $\theta$ are the galactocentric distance and azimuthal angle around the Galactic center, respectively ($\theta$ is defined as increasing clockwise), while $\psi$ is the pitch angle of the spiral field in the neighborhood of the solar system. We set $\psi = -10^\circ$. The field strength at a point $(r, \theta)$ in the Galactic plane (Stanev 1997) is

$$B(r, \theta) = \begin{cases} \left( B(r) \cos (\theta - \beta \ln \frac{r}{r_0}) \right), & \text{BS}, \\ B(r) \cos (\theta - \beta \ln \frac{r}{r_0}), & \text{AS}. \end{cases}$$  \hspace{1cm} (2)

Here $\beta = (\tan \psi)^{-1} = -5.67$ and $r_0 = 10.55$ kpc is the galactocentric distance of the location with maximum field strength at $l = 0^\circ$, which can be expressed as $r_0 = (R_G + d) \exp[-(\pi/2) \tan \psi]$, where $R_G = 8.5$ kpc is the distance of the solar system from the Galactic center and $d = 0.5$ kpc is the distance to the nearest field reversal from the solar system. Negative $d$ means that the nearest field reversal occurs in the direction of the Galactic center. Here $b(r_1)$ is the radial profile of the magnetic field strength. The radial profile is modeled by

$$b(r) = B_0 \frac{R_G}{r_1},$$  \hspace{1cm} (3)

where $B_0 = 4.4 \mu G$, which corresponds to 1.5 $\mu G$ in the neighborhood of the solar system. In the region around the Galactic center ($r_1 < 4$ kpc), the field is highly uncertain and thus assumed to be constant and equal to its value at $r_1 = 4$ kpc. The spiral field is assumed to be zero for $r_1 > 20$ kpc.
For the spiral halo field, we adopt an exponential decrease with two scale heights (Stanev 1997)

\[ B(r_{\|}, \phi, z) = B(r_{\|}, \phi) \begin{cases} \exp(-z), & 0 \text{ kpc} \leq z \leq 0.5 \text{ kpc}, \\ \exp\left(\frac{-z}{4} - \frac{3}{8}\right), & z > 0.5 \text{ kpc}, \end{cases} \]

where the factor \( \exp\left(-\frac{z}{2}\right) \) makes the field continuous on \( z \). The parity is represented as

\[ B(r_{\|}, \phi, -z) = \begin{cases} B(r_{\|}, \phi, z), & \text{S-type parity}, \\ -B(r_{\|}, \phi, z), & \text{A-type parity}. \end{cases} \]

In the GMF models with A-type parity, the direction of the spiral field is reversed below the Galactic plane. As a result, the spiral field is discontinuous at the Galactic plane. It is unphysical, but it is an approximate model reflecting observational results to support the A-type parity. Thus, we adopt such models to investigate the deflection of UHE protons. Note that GMF models with A-type parity predict symmetric trajectories of UHE protons about the Galactic plane even if the dipole field, introduced just below, is included.

Near the solar system, a vertical component of magnetic field with strength of 0.2–0.3 \( \mu G \), directed toward the northern Galactic pole, is observed (Han & Qiao 1994). Near the Galactic center, many nonthermal gaseous filaments perpendicular to the Galactic plane with tens of \( \mu G \) to mG have been discovered (Han 2007). These vertical magnetic fields indicate another regular component. In the dynamo theory, a dipole field is predicted with A-type parity in the so-called A0 mode. However, in this study, we assume that the z-component of magnetic field is a dipole field as

\[ B_x = -3 \mu G \sin \theta \cos \theta \cos \varphi / r^3, \]
\[ B_y = -3 \mu G \sin \theta \cos \theta \sin \varphi / r^3, \]
\[ B_z = \mu G (1 - 3 \cos^2 \theta) / r^3, \]

in all four models. Here \( \theta \) and \( \varphi \) are the zenith angle and the azimuthal angle in spherical coordinates centered at the Galactic center, respectively, and \( \mu G \sim 184.2 \ \mu G \text{kpc}^{-1} \) is the magnetic moment of the Galactic dipole, which is normalized at 0.3 \( \mu G \) in the vicinity of the solar system.

### 3. Distortion of UHE Sky

In this study, we investigate the deflection of UHE protons by the GMF. We adopt the backtracking method for calculation of UHE proton trajectories in the GMF. We inject protons with a charge of \(-1\) (called antiprotons below) from the Earth isotropically and follow their trajectories until the antiprotons reach a sphere of galactocentric radius of 40 kpc. The trajectories are regarded as those of protons coming from extragalactic space. All their energy loss processes are neglected, since the energy loss lengths are typically much shorter than the propagation path length in Galactic space.

Figure 1 shows plots of the velocity directions of antiprotons with \(10^{19.8} \text{eV} \) at 40 kpc from the Galactic center. These plots are calculated in the cases of the AS-S model (upper left), the AS-A model (upper right), the BS-S model (lower left), and the BS-A model (lower right). Each point is regarded as the arrival direction of an extragalactic proton, its source direction, before modification by the GMF.

All GMF models predict holes, where there are few arrival cosmic rays, within the radius of \( \sim 30^\circ \) in the direction of the Galactic center. Antiprotons injected from the Earth are strongly scattered around the Galactic center due to the strong dipole field. Thus, the arrival directions of protons coming from the direction around the Galactic center are quite different from their source positions (see also Fig. 3).

In the cases of GMF models with A-type parity, extragalactic protons coming from the direction around the Galactic plane also cannot reach the Earth. The main cause of this is the spiral magnetic field. The trajectories of protons arriving at the Earth are mainly affected by the spiral field in the Galactic disk and the dipole field around the Galactic center, since the strengths of these fields are strong. Antiprotons injected from the Earth are, at first, deflected by the disk field near the solar system. Antiprotons injected to positive latitude are deflected to lower latitude in the case of injection toward the direction of the Galactic center and to higher latitude in the case of injection toward the direction of the Galactic anticenter. Once antiprotons escape from the Galactic disk, they are minimally deflected by the weaker spiral field in the halo. Therefore, the spiral field in the neighborhood of the solar system mainly contributes to the global structure of the deflections. Moreover, A-type parity predicts symmetric trajectories about the Galactic plane. Thus, the antiprotons are driven out from
the Galactic disk region. The arrival directions of protons coming from the direction of the Galactic plane are quite different from their source positions. Comparing AS-A and BS-A models, the AS-A model predicts a larger region where extragalactic sources cannot contribute to the arrival protons. This is due to field reversals. In the AS models, the antiprotons keep on being deflected to the same directions due to no field reversals. On the other hand, the BS models have several field reversals. Once the antiprotons pass over a reversal point, they are deflected in the opposite direction to those just before. Therefore, the antiprotons are driven out less strongly from the Galactic disk region in the BS-A than in the AS-A model. In the GMF models with S-type parity, the deflections near the Galactic center cannot be positionally correlated with their extragalactic sources within a few degrees. If there is no dipole field, the regions with the deflections above 8° become much smaller, as shown in Kachelriess et al. (2007). We also discuss the effect of the dipole field in § 4.

Next, we investigate the deflection angles of protons during their propagation in Galactic space. In Figure 2, the injection directions of antiprotons with 10^{19.8} eV are plotted with the deflection angles shown in color in the online journal. In other words, the deflection experienced by a proton observed in the direction on the map is represented by the color of that point. Note that the deflection angle is defined as the separation angle between the injection direction of an antiproton and the direction of its velocity at 40 kpc from the Galactic center.

In any model, antiprotons injected in the direction of the Galactic center are strongly deflected above 8° by the dipole field near the Galactic center. This appears even if we consider antiprotons with 10^{20.0} eV. Consequently, protons with arrival directions near the Galactic center cannot be positionally correlated with their extragalactic sources within a few degrees. If there is no dipole field, the regions with the deflections above 8° become much smaller, as shown in Kachelriess et al. (2007). We also discuss the effect of the dipole field in § 4.

Except for the direction of the Galactic center, the distributions of the deflection angles of protons in both AS models are quite different from those in the BS models. In the AS models, protons from the direction around the Galactic plane are also deflected by more than 8°. This is because the spiral field without field reversals makes protons keep on being deflected in the same direction, unless protons are propagated across the Galactic plane. Protons coming from high Galactic latitudes are less deflected than those arriving from low latitudes, since the strong spiral field is localized in the Galactic disk. On the other hand, in the BS models, the deflection angles of protons arriving from the direction around the Galactic plane are smaller than those of protons arriving from high Galactic latitudes due to field reversals. Propagating protons are deflected to the opposite directions to those just before if they pass over a reversal point. These modifications of the deflections of their velocities make the overall deflection angles smaller. Protons coming from high Galactic latitudes are weakly affected by field reversals, since the strength of the spiral field in the halo is much weaker than that in the Galactic disk. If protons with 10^{20.0} eV are considered, the deflection angles become about a factor of 2 smaller. Except for the direction of the Galactic center, the deflection angles are allowed to be approximately proportional to the protons’ energy.

An intriguing structure is the regions at around (ℓ, b) ≈ (−60°, 20°) in both of the BS models and ≈ (−60°, −20°) in the BS-A model. The protons coming from these directions have very small deflection angles, since the deflections by the dipole field and the spiral field are balanced. In the former direction, there is Centaurus A (Cen A), which is the nearest radio-loud AGN. The Galactic coordinates are (ℓ, b) ≈ (−50°, 20°). Radio-loud AGNs are strongly motivated UHECR sources (Torres & Anchordoqui 2004). Moreover, PAO finds positional correlation of arrival directions of the highest energy events in the direction of Cen A (Pierre Auger Collaboration 2007). If Cen A is a source and the BS models reflect those of the real universe, then the spatial correlation between Cen A and the arrival directions of the highest energy cosmic rays should be expected. If the dipole field is weaker than that in this calculation, the regions with the smallest deflection angles are shifted a little lower in longitude, since the dipole field deflects antiprotons injected to higher longitude (Yoshiguchi et al. 2004).

Next, we investigate the deflection directions of extragalactic protons and the distortion of the extragalactic sky. Understanding the global structure of UHECR deflections is important for spatial correlation studies. For investigating the global structure of UHECR deflections, we calculate arrival directions of protons injected from sources arranged along several longitude lines and latitude lines.

Figure 3 shows the distortions of extragalactic longitude lines (left) and latitude lines (right). In the left panels, we plot the injection directions of antiprotons with 10^{19.8} eV whose velocity directions at 40 kpc from the Galactic center are ℓ = −120°, −60°, 0°, 60°, 120°, and 180°. Black indicates 0° longitude or latitude. These lines are regarded as the arrival directions of extragalactic protons with 10^{19.8} eV from sources distributed along the longitude lines.

![Figure 2](https://example.com/image2.png)

**Fig. 2.** Injection directions of antiprotons with 10^{19.8} eV in Galactic coordinates with the deflection angles shown in gray. Each point can be regarded as the arrival direction of a proton at the Earth with the deflection angle during its propagation in Galactic space. [See the electronic edition of the Journal for a color version of this figure.]
In any model, there are many points with different colors around the direction of the Galactic center. These are the arrival directions of protons that are strongly deflected by the dipole magnetic field around the Galactic center. As also shown in Figure 1, protons coming from the direction of the Galactic center arrive at the Earth from different directions in extragalactic space. These protons hardly contain information on the directions of their sources. About 5% of the events from the longitude lines of 60° and 300° and less than 3% of the events from the other three lines arrive from the direction of the Galactic center.

Longitude lines near the Galactic center are distorted. The longitude lines with \( \ell = 0° \) are highly distorted by the dipole field. The longitude lines with \( \ell = 60° \) and 300° are also distorted, but by the spiral field inside the solar system. Just inside the first field reversal interior to the solar system, there is a strong spiral field (see also Fig. 1 in Alvarez-Muñiz & Stanev 2006). The distortions depend on the direction of this spiral field. The other lines seem almost undistorted. However, protons are actually deflected along the longitude line. The difference in deflection between the GMF models is also apparent in the right panels.

The right panels show the distortions of five latitude lines with \( b = -60°, -30°, 0°, 30°, \) and 60°. Black indicates 0° longitude or latitude. The same method is used to describe the plots as in the left panels. The latitude lines are highly distorted, especially around the Galactic center. In the AS-A model, the latitude line with \( b = 0° \) disappears, since protons injected from extragalactic sources along the Galactic plane cannot reach the Earth, as also shown in Figure 1. In the BS-A model, that line almost disappears because of the same reason as in the AS-A model, but there are some points around the Galactic center. However, these protons are deflected by the dipole field above 10° during their propagation, as we can see in Figure 2. Antiprotons injected from the Earth to positive latitudes are deflected to higher latitude by the spiral field near the solar system in the case of injection toward the direction of the Galactic anticenter. Thus, the latitude lines with positive latitudes around the Galactic anticenter are distorted to lower latitudes. The deflections are stronger in the AS models than in the BS models due to no field reversal, as discussed above (see Fig. 2). In the southern Galactic hemisphere, the deflection directions are unchanged in GMF models with S-type parity. In the models with A-type parity, a symmetric pattern about the Galactic plane is predicted.

Finally, we investigate arrival directions of UHE protons from sources distributed along the supergalactic plane. In recent years, PAO rejected the hypothesis that the cosmic-ray spectrum continues in the form of a power law above the energies of \( 10^{19.6} \) eV with 6 \( \sigma \) significance (Yamamoto et al. 2007). This fact, i.e., confirmation of Greisen-Zatsepin-Kuz'min (GZK) steepening (Greisen
1966; Zatsepin & Kuz’min 1966), suggests astrophysical origins of UHECRs. Thus, the positional correlation between the arrival distribution of the highest energy cosmic rays and the supergalactic plane is expected if nearby astrophysical objects are UHECR sources. In the northern sky, the correlation between the arrival distribution of cosmic rays above $4 \times 10^{19}$ eV observed by four surface arrays (AGASA, Yakutsk, Haverah Park, and Volcano Ranch) and the supergalactic plane was pointed out with chance probability from a uniform distribution of less than 1% (Uchihori et al. 2000). Recent PAO results indicate such a correlation (Pierre Auger Collaboration 2007).

We investigate the deflections of protons injected from sources along the supergalactic plane by the GMF in order to revisit the correlation between the arrival directions and the supergalactic plane. Figure 4 shows the supergalactic plane and the arrival directions of protons with $10^{19.8}$ eV coming from the direction of the supergalactic plane (gray points). Practically, we plot the injection directions of antiprotons at the Earth whose velocity directions at 40 kpc from the Galactic center are toward the supergalactic plane with the gray points and the velocity directions as the supergalactic plane. Each color shows the angle deflected by the GMF as shown in Figure 2.

The supergalactic plane near the direction of the Galactic center is highly distorted by the spiral field inside the solar system and the dipole field. Except for the direction of the Galactic center, the deflection angles in the BS models are generally smaller than those in the AS models because of field reversals. The extragalactic universe is distorted mainly along the longitude lines, which reflects the local structure of the spiral field, except for the direction around the Galactic center. In GMF models with A-type parity, extragalactic protons coming from the direction around the Galactic plane cannot reach the Earth. In the BS models, protons coming from lower latitudes are deflected less than those coming from higher latitudes, since the latter do not experience modifications in their trajectories by field reversals. In the BS models, there are regions where the arrival directions are almost unchanged. One of the regions is near Cen A, which is the nearest radio-loud AGN and is a strong candidate of UHECR sources.

4. DEPENDENCE ON PARAMETERS IN THE GMF MODELS

In the previous section, we investigated the distortion of the UHE sky by the GMF in four different GMF models with the same parameter set. However, the values of the parameters include some uncertainty. In this section, we discuss the dependence of the deflections of protons on such parameters.

Figure 5 shows the same plots as Figure 2, but using different parameters in the AS-S and the BS-S models. A recent analysis of Faraday rotation measures suggests an exponential radial profile of magnetic field strength (Han et al. 2006). Accordingly, we adopt the exponential profile proposed in Han et al. (2006) as

$$b(r) = B_0 \exp \left[ -\frac{r - R_0}{r_s} \right],$$

where $r_s = 8.5$ kpc is the scale radius. Figure 5 (left) represents the maps of the deflection angles calculated in the GMF models with this exponential radial profile. The global structure is unchanged.

The pitch angle also includes some uncertainty. We adopt $P = -10^\circ$. While this is the same value as in previous studies (Alvarez-Muñiz et al. 2002; Takami et al. 2006), the calculations by Tinyakov & Tkachev (2002) and Prouza & Smida (2003) adopted $P = -8^\circ$. Therefore, we should check the dependence on the pitch angle here. Figure 5 (right) shows the deflection angles calculated in the GMF models with $P^{-1}$ profile defined as in § 2 with $P = -8^\circ$. Here $B_0$ is set to $3.6 \mu$G, which corresponds to $1.5 \mu$G near the solar system.
An interesting change is that the deflection angles in the direction of the Galactic anticenter are smaller than those in the models with \( p = -10^\circ \), especially in the BS-S model. The reason is the positioning of a field reversal just outside the solar system. In the spiral field model that we use, the nearest field reversal inside the solar system exists at \( d = -0.5 \text{kpc} \), which is fixed as a model parameter. This value is plausible based on many observations. On the other hand, the field reversals outside the solar system have weaker evidence. When \( p \) is changed, the field reversal points are changed except for the nearest one in the model. In particular, the field reversal point just outside the solar system, which affects the deflection angles of protons arriving from the direction of the Galactic anticenter, becomes nearer than that in the case of \( p = -10^\circ \). Antiprotons injected to the Galactic anticenter are deflected to higher latitude by the spiral field in the neighborhood of the solar system. When the antiprotons reach the field reversal, the directions of the deflection are opposite and the trajectories are modified to their injection directions. If the field reversal is nearer, that modification is relatively stronger. Thus, the deflection angles are smaller than those in the case of \( p = -10^\circ \). In the AS-S model, similar tendencies can be found. By definition, the spiral field is weak near points that correspond to field reversals in the BS model. The deflection angles of antiprotons injected in the direction of the Galactic anticenter are smaller, since the region with weak magnetic field approaches the solar system in the case of \( p = -8^\circ \).

Finally, we investigate the effect of the dipole field. Figure 6 shows the same figure as Figure 3, but the dipole field is not included. As parameters of the spiral field, the same set as those in §3 are adopted. Compared to Figure 3, the highly deflected events around the direction of the Galactic center disappear. Antiprotons are less deflected, since the spiral field is much weaker than the dipole field near the Galactic center. However, because the magnetic strength of the spiral field reaches near \( 10^{19.8} \mu \text{G} \) around the Galactic center, large deflections along the longitude lines are experienced by protons with their arrival directions around the Galactic center. On the other hand, protons coming from the directions of the Galactic anticenter are almost unchanged, since the dipole field is very weak outside the Galactic center region.

5. DISCUSSION AND CONCLUSION

In this study, we investigate the deflections in Galactic space of UHE extragalactic protons above \( 10^{19.8} \text{eV} \) by calculating their propagation in four different GMF models using the backtracking method in order to discuss the correlation between the arrival directions of UHECRs and their source positions. Protons arriving from the direction around the Galactic center are highly deflected by a dipole magnetic field. Source positions of such

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**Fig. 5.**—Same as Fig. 2, but in the cases of the AS-S and BS-S models with an exponential radial profile of GMF strength (left) and \( p = -8^\circ \) (right). [See the electronic edition of the Journal for a color version of this figure.]

**Fig. 6.**—Same as Fig. 3, but in the case of no dipole field. [See the electronic edition of the Journal for a color version of this figure.]
protons are quite different from their arrival directions. Thus, the direction of the Galactic center is not suitable for correlation studies. If a correlation is found in the direction of the Galactic center, we can obtain a strong constraint on the GMF around the Galactic center. In the BS models, there are directions where the arrival directions are almost unchanged. One of these directions is toward Cen A, which is the nearest radio-loud AGN and a strong candidate of UHECR sources. If Cen A is confirmed as a UHECR source, the BS models with dipole field are confirmed as a possible model of the GMF.

Except for the direction of the Galactic center, global structures of the deflection directions are determined by the spiral field. The trajectories of protons are deflected mainly along the longitude lines. The BS models yield smaller deflection angles than the AS models due to field reversals of the spiral magnetic field. In the AS models, without any field reversals, the deflection angles of protons are large, since protons are continuously deflected in the same directions.

In the direction around the Galactic anticenter, the deflection angles are relatively small for the BS models. They become smaller by adopting a smaller pitch angle, \( p = -8^\circ \), since the field reversal outside the solar system is nearer. Thus, the Galactic anticenter region with \( |b| < 30^\circ \) is the best region for correlation studies. This region is in the Northern Hemisphere, where PAO cannot detect UHECRs.

We also investigate the distortion of the supergalactic plane by the GMF. The supergalactic plane near the Galactic center is highly distorted, and the pattern of the distortion is dependent on the spiral field model. Ide et al. (2001) showed that one can check whether the UHECR source distribution is correlated with the supergalactic plane by \( O(10^3) \) event detection over the entire sky. This claim is based on UHECR propagation in extragalactic space. If the positional correlation between the arrival distribution and the supergalactic plane is found in the future, we can obtain information on the global structure of the GMF. On the other hand, the supergalactic plane near the Galactic anticenter is less distorted than that near the Galactic center, although the arrival protons are strongly deflected along the longitude line in the AS models. In the Northern Hemisphere, which contains the Galactic anticenter, the correlation between the arrival distribution and the supergalactic plane can be tested, which is weakly dependent on the spiral field model.

As discussed above, the Northern Hemisphere is more suitable for positional correlation studies. The direction of the Galactic anticenter does not bother us with uncertainty of magnetic fields around the Galactic center. In our previous study, we predicted the positional correlation between UHECR arrival directions and positions of local sources at a scale of \( 2^\circ \times 2^\circ \), taking into account only EGMF (Takami & Sato 2008). Adding the results of this study, we can predict the spatial correlation at a scale of \( \sim 4^\circ \) for the BS-S model with \( p = -8^\circ \) and \( \sim 6^\circ \) for the same with \( p = -10^\circ \) in the direction around the Galactic anticenter. If the AS model is a real situation, regions where we can find positional correlation on small angular scales are highly constrained.

In the Northern Hemisphere, Telescope Array is under construction and will start observation in the near future (Fukushima et al. 2007). PAO also projects its northern site with larger exposure than its southern site (Nitz et al. 2007). The Extreme Universe Space Observatory (JEM-EUSO), which can detect UHECRs from the International Space Station with extremely large exposure, is also projected (Ebisuzaki et al. 2007). The southern site of PAO will strongly contribute to our understanding of the nature of UHECRs and their sources. As a next step for UHECR astronomy, these detectors will play a crucial role for understanding UHECR sources by observations in the northern sky in which the deflection angles of UHECRs are smaller.

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