ARRIVAL DISTRIBUTION OF ULTRA–HIGH-ENERGY COSMIC RAYS: PROSPECTS FOR THE FUTURE
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ABSTRACT

We predict the arrival distribution of ultra–high-energy cosmic rays (UHECRs) above $4 \times 10^{19}$ eV with the event number expected by future experiments in the next few years. We perform event simulations with the source model that is adopted in our recent study and can explain the current Akeno Giant Air Shower Array (AGASA) observation. At first, we calculate the harmonic amplitude and the two-point correlation function for the simulated event sets. We find that significant anisotropy on a large angle scale will be observed when $\sim 10^7$ cosmic rays above $4 \times 10^{19}$ eV are detected by future experiments. The Auger array will detect cosmic rays with this event number in a few years of operation. The statistics of the two-point correlation function will also increase. The angle scale at which the events have strong correlation with each other corresponds to the deflection angle of UHECRs propagating in the extragalactic magnetic field (EGMF), which in turn can be determined by the future observations. We further investigate the relation between the number of events clustered in a direction and the distance of their sources. Despite the limited amount of data, we find that the C2 triplet events observed by the AGASA may originate from a source within 100 Mpc from us at $2 \sigma$ confidence level. Merger galaxy Arp 299 (NGC 3690 + IC 694) is the best candidate for their source. If data accumulate, the UHECR sources within $\sim 100$ Mpc can be identified significantly from observed event clusterings. This will provide some kinds of information about poorly known parameters that influence the propagation of UHECRs, such as extragalactic and Galactic magnetic fields and the chemical composition of observed cosmic rays. Also, we will reveal the origin of UHECRs with our method of identifying their sources. Finally, we predict the arrival distribution of UHECRs above $10^{20}$ eV that is expected to be observed if the current HiRes spectrum is correct and discuss their statistical features and implications.

Subject headings: cosmic rays — galaxies: general — ISM: magnetic fields — large-scale structure of universe — methods: numerical

1. INTRODUCTION

The Akeno Giant Air Shower Array (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 Greisen-Zatsepin-Kuz'min (GZK) cutoff (Greisen 1966; Zatsepin & Kuz'min 1966) because of photopion production with the photons of the cosmic microwave background (CMB), and it extends above $10^{20}$ eV (Takeda et al. 1998). On the other hand, the arrival distribution of UHECRs seems to be isotropic on a large scale, with a statistically significant small-scale clustering (Takeda et al. 1999). The current AGASA data set of 57 events above $4 \times 10^{19}$ eV contains four doublets and one triplet within a separation angle of $2^\circ$5. The chance probability of observing such clusters under an isotropic distribution is only about 1% (Hayashida et al. 2000).

Recently, the High Resolution Fly’s Eye (HiRes; Wilkinson et al. 1999) reports the cosmic-ray flux with the GZK cutoff around $10^{20}$ eV (Abu-Zayyad et al. 2002). At present, it is very difficult to draw a conclusion about the existence or nonexistence of the GZK cutoff, because the two experiments have detected only a handful of events above this energy. On the other hand, there are new large-aperture detectors under development, such as the South and North Auger project (Capelle et al. 1998), the Extreme Universe Space Observatory (EUSO; Benson & Linsley 1982), and the Orbiting Wide-Angle Light Collectors (OWL; Cline & Stecker 2000) experiments. The detection or non-detection of the GZK cutoff in the cosmic-ray spectrum remains open to investigation by these future-generation experiments.

Potential models of UHECR origin are constrained by their ability to reproduce the measured energy spectrum and the arrival distribution observed by the AGASA. In our recent work (Yoshiguchi et al. 2003b, hereafter Paper I), we perform numerical simulations for propagation of ultra-high-energy (UHE) protons in intergalactic space and examine whether the present AGASA observation can be explained by a bottom-up scenario in which the source distribution of UHECRs is proportional to that of galaxies. We use the Optical Redshift Survey (ORS; Santiago et al. 1995) to construct realistic source models of UHECRs. We can construct realistic source models of UHECRs by using the galaxy sample because the astrophysical candidates for UHECR sources, such as active galactic nuclei (AGNs; Halzen & Zas 1997), gamma-ray bursts (GRBs; Waxman 1995, 2000), and colliding galaxies (Cesarsky 1992; Smailkowsi, Giller, & Michalak 2002), are connected to galaxies. For example, AGNs are considered supermassive black holes in the centers of the galaxies, a GRB occurs in a galaxy, and so on.

In Paper I, we calculate both the energy spectrum and arrival directions of UHE protons, and compare the results with the AGASA observation. We find that the arrival distribution of UHECRs becomes most isotropic when sources are restricted to luminous galaxies ($M_{\text{lim}} = -20.5$). This is

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because luminous galaxies in the Local Supercluster (LSC) are distributed more widely than faint galaxies, contrary to general clusters of galaxies (Yoshiguchi et al. 2003a). However, it is not isotropic enough to be consistent with the AGASA observation, even for $M_{\text{lim}} = -20.5$. In order to obtain a sufficiently isotropic arrival distribution, we randomly select sources more luminous than $-20.5$ mag from the ORS sample that contribute to the observed cosmic-ray flux and find that the isotropic arrival distribution of UHECRs can be reproduced when $\sim 1/50$ of the sample are selected as UHECR sources. In terms of the source number density, this constraint corresponds to $\sim 10^{-6} \text{ Mpc}^{-3}$.

We further find that the small-scale anisotropy cannot be well reproduced in the case of strong extragalactic magnetic fields (EGMFs; $B \geq 10$ nG). This is because the correlation on small scales between events that originate from a single source is eliminated, or the correlation continues on a larger angle scale, as a result of the large deflection angle when UHECRs propagate in EGMFs from their sources to the Earth.

However, we should comment on the studies by other workers. Isola & Sigl (2002) and Sigl, Miniati, & Ensslin (2003) study the propagation of UHE protons in strong EGMFs ($\sim 1 \mu G$) in the LSC, assuming local enhancement of UHECR sources in the LSC. The strong EGMFs of $\sim 1 \mu G$ lead to substantial deflection of UHECRs, which is better for explaining the observed isotropic distribution of UHECRs. However, the consistency of both the small- and large-scale isotropy predicted by their scenarios with the AGASA observation is marginal and somewhat worse than that predicted by our scenario in Paper I. There are also suggestions that the observed energy spectra have the imprints of UHE proton interaction with the CMB photons in the form of the beginning of the GZK cutoff at $E \sim 4 \times 10^{19}$ eV (Berezhnsky, Gazizov, & Grigor’eva 2002b, 2003; de Marco, Blasi, & Olinto 2003). In the presence of local enhancement of UHECR sources in the LSC, this feature of the observed spectra seems to be difficult to reproduce. The AGASA observation may imply that UHECRs propagate along nearly straight lines in intergalactic space. However, we cannot draw any firm conclusions because of the limited amount of data. The next-generation experiments will clarify the situation with a large amount of data.

If local enhancement of UHECR sources in the LSC (Sigl, Lemoine, & Biermann 1999; Lemoine, Sigl, & Biermann 1999; Isola & Sigl 2002; Sigl 2003; Sigl et al. 2003) is disfavored by the observations, there is no way to explain the observed extension of the cosmic-ray spectrum beyond the GZK cutoff. Our conclusion in Paper I 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 mentioned above, many future experiments are under development. These experiments will provide us a large amount of data, at least below $10^{20}$ eV, and allow us to discuss the features of the arrival distribution of UHECRs and determine which model of UHECR origin can explain the observations with better statistical significance. In this paper, we predict the arrival distribution of UHECRs above $4 \times 10^{19}$ eV with the event number expected by future experiments in the next few years. We perform event simulations with the source model that can explain the current AGASA observation. It is noted that our prediction is not the exact arrival direction of each UHECR but the statistical features of the arrival distribution, because there are degrees of freedom in randomly selecting the UHECR sources from the ORS sample. First, we examine how much the future experiments decrease the statistical uncertainty of the cosmic-ray spectrum at the highest ($\sim 10^{20}$ eV) energies (de Marco et al. 2003). Next, we calculate the harmonic amplitude and the two-point correlation function and demonstrate that observational constraints on the model of UHECR origin become severer with new experiments. We further investigate the relation between the number of events clustered in a direction and the distance of their source. Such analysis has never been performed before. Implications of the results are discussed in detail. Finally, we also predict the arrival distribution of UHECRs above $10^{20}$ eV that is expected to be observed if the current HiRes spectrum is correct and discuss its statistical features and implications.

In § 2, we describe our method of calculation. Results are shown in § 3. In § 4, we summarize the main results and discuss their implications.

2. NUMERICAL METHOD

2.1. Numerical Simulation

This subsection provides the method of Monte Carlo simulations for propagation of UHE protons in intergalactic space. We use the same numerical approach used in Paper I. Detailed explanations are presented in Paper I.

UHE protons below $\sim 8 \times 10^{19}$ eV lose their energies mainly by pair creation and above that level by photopion production (Berezinsky & Grigor’eva 1988; Yoshida & Teshima 1993) 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 Chodorowski, Zdziarski, & Sikora (1992) to calculate the energy loss rate for the pair production on isotropic photons. On the other hand, protons lose a large fraction of their energy in photopion production. For this reason, 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 (Mücke et al. 2000).

EGMFs are little known theoretically and observationally. There is an upper limit for the strength and correlation length for the universal EGMF, $B / c (r / (1 \text{ Mpc}))^{1/2} < 1 \text{ nG}(1 \text{ Mpc})^{1/2}$, as measured by Faraday rotation of radio signals from distant quasars (Kronberg 1994). However, simple analytical arguments based on magnetic flux freezing and large-scale structure simulations passively including the magnetic field (Kulsrud et al. 1997) demonstrate that the magnetic field is most likely as structured as are the baryons. Local EGMFs as strong as $\sim 1 \mu G$ in sheets and filaments of large-scale galaxy distribution, as in the LSC, are compatible with existing upper limits on Faraday rotation (Ryu, Hang, & Biermann 1998; Blasi, Burles, & Olinto 1999). It is suggested that the arrival distribution of UHECRs depends on the fields in the immediate environment of the observer.

However, we may expect that the effects of such strong EGMFs on UHECR arrival directions could be small in our source scenario. In the source model by Isola & Sigl (2002) and Sigl et al. (2003), all sources are assumed to be in the
LSC. Thus, in their model the effect of strong EGMFs on the deflection angles of UHECRs is reported to be large. On the contrary, we show in Paper I that a source number density of $\sim 10^{-6}$ Mpc$^{-3}$ is favored in order to explain the arrival distribution of UHECRs observed by the AGASA. In this case, there is no source in the LSC. Accordingly, almost all of the paths of the observed UHECRs from sources to the Earth are not in the LSC but outside it in our model, because the structure of strong EGMFs in the LSC would be like a two-dimensional sheet of large-scale galaxy distribution, as shown in Sigl et al. (2003). We also note that Faraday rotation measurement gives not the absolute value of the strength of the EGMF, but only its upper limit.

We further find that small-scale clustering cannot be well reproduced in the case of strong EGMFs ($B > 10$ nG). If the local strong EGMF affects the arrival directions of UHECRs, small-scale clustering observed by the AGASA may not be obtained. Thus, we assume that the local strong EGMF in the LSC, even if it exists with the structure like a two-dimensional sheet, does not affect the arrival directions of UHECRs, and we adopt a homogeneous random turbulent magnetic field with $(B, l_c) = (1$ nG, $1$ Mpc).

Of course, we cannot draw conclusions on the effects of strong EGMFs, considering the limited amount of observed data. However, since the model of local enhancement of UHECR sources (Isola & Sigl 2002; Sigl et al. 2003) predicts the emergence of large-scale anisotropy that reflects the spatial structure of the LSC, we will be able to draw firm conclusions by comparing the prediction of the source scenario presented in this paper with the results of the future experiments. This is one of the purposes of the present study.

We also note that numerical simulations of UHECR propagation in inhomogeneous EGMFs over cosmological distances are highly time-consuming. (On the other hand, Isola & Sigl 2002 and Sigl et al. 2003 perform numerical simulations of UHECR propagation over $\sim 50$ Mpc.) With the assumption of a homogeneous EGMF, we can perform numerical simulation of UHECR propagation under spherical symmetry. Provided that the EGMF is inhomogeneous, however, the propagation of UHECRs from a single point source no longer has spherical symmetry. As a result, we have to specify the Earth’s position in the universe. We also have to choose the detector (Earth) size small enough for us to accurately calculate the arrival directions. In this case, the number fraction of injected UHECRs arriving at the Earth is extremely small. This requires the number of propagating particles to be several orders of magnitudes higher than that used in this study, which takes enormous CPU time. Detailed study on the effects of a strong EGMF in the LSC are beyond the scope of this paper and left for future study.

We assume a turbulent magnetic field with power-law spectrum $\langle B^2(k) \rangle \propto k^{n_H}$ for $2\pi/l_c \leq k \leq 2\pi/l_{cut}$ and $\langle B^2(k) \rangle = 0$ otherwise, where $l_{cut}$ characterizes the numerical cutoff scale. We use $n_H = -11/3$, corresponding to the Kolmogorov spectrum. Physically, one expects $l_{cut} \ll l_c$, but we set $l_{cut} = \frac{1}{4} l_c$ in order to save CPU time. The universe is covered with cubes of side $l_c$. For each of the cubes, Fourier components of the EGMF are dialed on a cubic cell in wavenumber space, whose side is $2\pi/l_c$, with random phases according to the Kolmogorov spectrum, and then Fourier transformed onto the corresponding cubic cell in real space. We create an EGMF of $20 \times 20 \times 20$ cubes of side $l_c$ and, outside it, adopt the periodic boundary condition in order to reduce data storage for magnetic field components. Similar methods for turbulent magnetic fields have been adopted (Sigl et al. 1999; Lemoine et al. 1999; Isola & Sigl 2002).

In this study, we neglect the effects of the Galactic magnetic field. We will conduct studies on its effects in forthcoming paper.

Finally, we explain how the energy spectrum and the arrival directions of UHECRs are calculated. First, protons with a flat energy spectrum are injected isotropically at a given point within the range of $10^{19.5}-10^{22}$ eV. Five thousand protons are injected in each of 26 energy bins, that is, 10 bins per decade of energy. Then, UHE protons are propagated in the EGMF over 1 Gpc for 15 Gyr. Weighted with a factor corresponding to an $E^{-2}$ power-law spectrum, this provides the distribution of energy, deflection angle, and time delay of UHECRs as functions of the distance from the initial point. In this paper, we use the distribution of energies and deflection angles integrated over the time delay, assuming that the cosmic-ray flux at the Earth is stationary. With this distribution, we can calculate the energy spectrum and the arrival directions of UHECRs injected at a single UHECR source. Then, summing contributions from all the sources (see § 2.2), we obtain the angular probability distribution of UHECRs as a function of their energies. According to this angular probability distributions, we simulate the energy spectrum and the arrival directions of UHECRs.

2.2. Source Distribution

In this study, we assume that the source distribution of UHECRs is proportional to that of the galaxies. We use the realistic data from the ORS (Santiago et al. 1995) galaxy catalog. As mentioned in § 1, we show in Paper I that the arrival distribution of UHECRs observed by the AGASA can be reproduced when $\sim 1/50$ of the ORS galaxies more luminous than $M_{lim} = -20.5$ are selected as UHECR sources. We consider only the predictions of this source model throughout the paper. It is unknown how much an ultimate UHECR source contributes to the observed cosmic-ray flux. In Paper I, we thus consider two cases, in which (1) all galaxies are the same or (2) they inject cosmic rays proportionally to their absolute luminosity. However, we find that the results in these two cases do not differ from each other, insofar as we focus on the luminous galaxies as UHECR sources. Accordingly, we restrict ourselves to the case in which all galaxies inject the same amount of cosmic rays.

In order to calculate the energy spectrum and the distribution of arrival directions of UHECRs realistically, there are two key elements of the galaxy sample to be corrected. First, galaxies in a given magnitude-limited sample are biased tracers of matter distribution because of the flux limit. Although the sample of galaxies more luminous than $-20.5$ mag is complete within $80$ h$^{-1}$ Mpc (where $h$ is the Hubble constant divided by 100 km s$^{-1}$ and we use $h = 0.75$), it does not contain galaxies outside it because of the selection effect. We distribute sources of UHECRs outside $80$ h$^{-1}$ Mpc homogeneously and calculate their number from the number of galaxies within that distance. Second, our ORS sample does not include galaxies in the zone of avoidance ($|b| < 20^\circ$). In the same way, we distribute UHECR sources in this region homogeneously and calculate their number density from the number of galaxies in the observed region.
2.3. Statistical Methods

In this subsection, we explain three statistical quantities: the harmonics analysis for large-scale anisotropy (Hayashida et al. 1999), the two-point correlation function for small-scale anisotropy, and the correlation value for investigation of the correlation between the events and their sources defined in our previous study (Ide et al. 2001).

The harmonic analysis to the right-ascension distribution of events is the conventional method of searching for global anisotropy of cosmic-ray arrival distribution. For a ground-based detector like the AGASA and the Auger array, almost uniform observation in right ascension is expected. The \( m \)th harmonic amplitude \( r \) is determined by fitting the distribution to a sine wave with period \( 2\pi/m \). For a sample of \( n \) measurements of phase, \( \phi_1, \phi_2, \ldots, \phi_n \) \( (0 \leq \phi_i \leq 2\pi) \), it is expressed as

\[
r = (a^2 + b^2)^{1/2},
\]

where \( a = (2/n)\sum_{i=1}^{n}\cos m\phi_i \) and \( b = (2/n)\sum_{i=1}^{n}\sin m\phi_i \). We calculate the harmonic amplitude for \( m = 1 \) to \( 4 \) from a set of events generated according to the predicted probability density distribution of arrival directions of UHECRs.

If a total number of \( n \) events are uniformly distributed in right ascension, the chance probability of observing the amplitude \( \geq r \) is given by

\[
P = \exp(-k),
\]

where

\[
k = nr^2/4.
\]

The 57 AGASA events are consistent with isotropic source distribution, within a 90% confidence level (Takeda et al. 1999; Hayashida et al. 2000). We therefore compare the harmonic amplitude for \( P = 0.1 \) with the model prediction and estimate the event number at which large-scale anisotropy of the UHECR arrival distribution becomes significant.

The two-point correlation function \( N(\theta) \) contains information on the small-scale anisotropy. We start from a set of generated events or the actual AGASA data. For each event, we divide the sphere into concentric bins of angular size \( \Delta \theta \) and count the number of events falling into each bin. We then divide it by the solid angle of the corresponding bin, that is,

\[
N(\theta) = \frac{1}{2\pi\cos \theta - \cos(\theta + \Delta \theta)} \sum_{\theta \leq \phi \leq \theta + \Delta \theta} 1 \text{ (sr}^{-1}),
\]

where \( \phi \) denotes the separation angle of the two events; \( \Delta \theta \) is taken to be \( 1^\circ \) in this analysis. The AGASA data show strong correlation at small angles \( (-2^\circ), \) with a 5 \( \sigma \) significance of deviation from an isotropic distribution (Takeda et al. 1999; Hayashida et al. 2000).

We use the correlation value defined in our previous study (Ide et al. 2001) in order to investigate statistically the similarity between the arrival distribution of UHECRs and the source distribution. The correlation value \( \Xi \) between two distributions, \( f_e \) and \( f_s \), is defined as

\[
\Xi(f_e, f_s) \equiv \frac{\rho(f_e, f_s)}{\sqrt{\rho(f_e, f_e)\rho(f_s, f_s)}},
\]

where

\[
\rho(f_a, f_b) = \sum_{j,k} \frac{f_a(j, k) - \bar{f}_a}{f_a} \frac{f_b(j, k) - \bar{f}_b}{f_b} \Delta \Omega(j, k)/4\pi.
\]

Here subscripts \( j \) and \( k \) distinguish each cell of the sky, \( \Delta \Omega(j, k) \) denotes the solid angle of the \( (j, k) \) cell, and \( \bar{f} \) means the average of \( f \). In equation (5), \( f_e \) and \( f_s \) represent the distributions of the simulated events and the sources, respectively. In this study, the size of the cell is chosen to be \( 1^\circ \times 1^\circ \). The meaning of \( \Xi \) is as follows. By definition, \( \Xi \) ranges from \(-1 \) to \(+1 \). When \( \Xi = +1 \) \((-1 \) \), the two distributions are exactly the same (opposite). When \( \Xi = 0 \), we cannot find any resemblance between the two distributions.

3. RESULTS

3.1. Statistical Significance of the Energy Spectrum at \( \sim 10^{20} \text{ eV} \)

Before we discuss the future prospects of the UHECR arrival distribution, we examine how much the future experiments decrease the statistical uncertainty of the cosmic-ray spectrum at the highest energy range \( \sim 10^{20} \text{ eV} \). In Figure 1, we show the energy spectrum predicted by a specific source scenario in which 1/50 of the ORS galaxies more luminous than \( M_{\text{lim}} = -20.5 \) are selected as UHECR sources. The injection spectrum is taken to be \( E^{-2} \).

![Fig. 1.—Energy spectrum with injection spectrum \( E^{-2} \) predicted by a specific source scenario when 1/50 of the ORS galaxies more luminous than \( M_{\text{lim}} = -20.5 \) are selected as UHECR sources. The simulations are performed with the fixed event numbers above \( 4 \times 10^9 \text{ eV} \). The shaded region indicates the statistical error due to the finite number of simulated events. We also show the cosmic-ray spectra observed by HiRes (Abu-Zayyad et al. 2002) and AGASA (Hayashida et al. 2000).](image-url)
Berezinsky, Gazizov, & Grigor’eva (2002a) show that predicted flux of UHECRs falls short of the observed flux below $10^{19.5}$ eV in the case of injection spectrum $E^{-2}$. However, there may be UHECR production sites in which maximum energy of cosmic rays achieved is lower than $10^{19.5}$ eV. These components may substantially contribute to the cosmic-ray flux below $10^{19.5}$ eV. Throughout the paper, we assume that these components bridge the gap between the observed flux and that predicted with the injection spectrum $E^{-2}$ and restrict ourselves to cosmic rays above $10^{19.5}$ eV.

In Figure 1, event simulations are performed with the fixed event numbers above $4 \times 10^{19}$ eV. Typically, we perform 10,000 such simulations. The shaded region indicates the statistical error due to the finite number of simulated events. The spectrum measured by HiRes is consistent with our model prediction, while that of the AGASA is not. However, the statistical significance of deviation from the prediction of our source scenario is about only $\sim 2$ $\sigma$. The region of the energy spectrum dominated by statistical fluctuation moves to higher energies with an increasing amount of data, as shown in Figure 2. It is noted that future experiments, such as the Auger and the EUSO/OWL, would detect $\sim 500$ and $\sim 5000$ events above $4 \times 10^{19}$ eV yr$^{-1}$, respectively. These high statistics will allow us to reach conclusions about the presence or absence of the GZK cutoff in the cosmic-ray spectrum in the next few years. A similar conclusion is obtained by de Marco et al. (2003).

3.2. Arrival Distribution of UHECRs

In this subsection, we present the results of the numerical calculations for the arrival distributions of UHECRs. Figure 3 shows realizations of the UHECR arrival direction above $4 \times 10^{19}$ eV predicted by a specific source scenario in which $1/50$ of the ORS galaxies more luminous than $M_{\lim} = -20.5$ are randomly selected as UHECR sources. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100 Mpc are shown with bold circles. Throughout the paper, we show the results only for this specific source scenario. We have checked that the results do not depend very much on the realization of the source selection, unless extremely nearby sources ($<30$ Mpc) are accidentally selected. We note that the current AGASA data set include 49 events with energies of $4 \times 10^{19}$–$10^{20}$ eV in the range of $-10^\circ \leq \delta \leq 80^\circ$. This event number corresponds to 100 events in Figure 3, where we do not restrict the arrival directions of UHECRs to any range of $\delta$.

A visual inspection of Figure 3 reveals no significant large-scale anisotropy. We show the harmonic amplitude as a function of the event number for $m = 1$–4 in Figure 4. We plot the average over all trials of the event realizations from the calculated probability distribution with the statistical error. In order to obtain the average and the variance, we dial the simulated sets of events 20–1000 times, depending on the total event number. The solid line in this figure represents the values of $r$ in equation (3) for $P = 0.1$ (eq. [2]). Of course, this region becomes smaller with increasing event number.

At present, our source model predicts a harmonic amplitude consistent with the isotropic source distribution. However, future experiments will separate our model prediction from the isotropic source at a confidence level of 90% with an event number of the order of $\sim 10^3$. It is also found that the amplitude for $m = 1$ is smaller than that for another values of $m$. The amplitude for larger $m$ quantifies anisotropy on a smaller scale. Therefore, this dependence on $m$ reflects the fact that the arrival distribution shown in Figure 3 reveals the distribution of their sources as the event number increases, in that the event clusterings occur in the directions of the nearby ($<100$ Mpc) sources. This feature of the UHECR arrival distribution is discussed below in detail.

In this source scenario, the small-scale anisotropy observed by the AGASA is also reproduced, as is evident from Figure 5, where the two-point correlation functions of the simulated events are shown. The error bars represent the statistical fluctuations due to the finite number of the simulated events. For the event number of 100, we also show the two-point correlation function of the 49 AGASA events in the energy range $4 \times 10^{19}$–$10^{20}$ eV, multiplied by factor of 2 in order to compensate for the difference in the range of $\delta$ between the observation and the numerical calculation. The slight shrinkage of $N(\delta)$ in the smallest angle bin is due to the manner of dividing the sphere into concentric bins when taking the data of numerical simulations of UHECR propagation.

Since the small-scale anisotropy is due to the pointlike nature of UHECR sources, the angle scale at which there is strong correlation between the events corresponds to the deflection angles of UHECRs propagating in EGMFs from sources to the Earth. Figure 5 demonstrates that, for the amount of data expected with next-generation experiments, the statistical uncertainty will considerably decrease. This will clarify the angle scale at which the events have a strong correlation with each other. Accordingly, we will be able to
**Fig. 3.** Arrival directions of UHECRs above $4 \times 10^{19}$ eV predicted by a specific source scenario when 1/50 of the ORS galaxies more luminous than $M_{\text{lim}} = -20.5$ are selected as UHECR sources. Distribution of selected sources within 200 Mpc is also shown as circles of radius inversely proportional to their distances. Only the sources within 100 Mpc are shown with bold circles.

**Fig. 4.** Harmonic amplitude predicted by a source model of Fig. 3 as a function of the total number of events. Error bars represent the statistical fluctuations due to the finite number of the simulated events. The region below the solid line is expected from the statistical fluctuation of isotropic source distribution with the chance probability larger than 10%.

**Fig. 5.** Two-point correlation functions predicted by a source model of Fig. 3. Error bars represent the statistical fluctuations due to the finite number of the simulated events. For the event number of 100, we also show the two-point correlation function for the 49 AGASA events in the energy range $4 \times 10^{19} - 10^{20}$ eV, multiplied by factor of 2 in order to compensate for the difference of the range $\delta$ between the observation and the numerical calculation.
determine the strength of the universal EGMF from the two-point correlation function of observed UHECRs, with a sufficient amount of data.

As mentioned above, our source model predicts the statistically significant small-scale anisotropy, which correlates with the sources located within 100 Mpc, with a large amount of data (see Fig. 3). What is deduced from this feature about the origin of UHECRs? To begin with, we quantitatively examine the relation between the event distribution and the source distribution. The top panel of Figure 6 shows the correlation value defined in § 2.3 between the distribution of events above $4 \times 10^{19}$ eV and the distribution of sources within 100, 200, and 300 Mpc as a function of the event number. The results for the events above $10^{20}$ eV are discussed in § 3.3. The error bars have the same meaning as in Figure 4.

Clearly visible in this figure is that the correlation of the event distribution with the source distribution is strongest for the sources within 100 Mpc. This strong correlation is due to the event sets that cluster in the direction of the sources within 100 Mpc (see Fig. 3). The number of clustered events fluctuates with every realization, and this number is a critical factor for the correlation with the sources within 100 Mpc. On the other hand, this number does not affect the correlation with the sources within larger distances very much, because there are a number of sources in this case. Therefore, the statistical error is smaller for the correlation with the sources at larger distances. When the event number is close to the order of several times $10^3$, the correlation values begin to converge, and the final values can be estimated. We emphasize that the expected event rate from the Auger observation is $\sim 500$ yr$^{-1}$. After several years of observation with the Auger array, we would be able to know the source distribution within $\sim 100$ Mpc.

Here we note that the UHECR sources outside 107 Mpc ($\approx 80 h^{-1}$ Mpc) in our model are randomly distributed, as mentioned in § 2.2. We should compare the correlation function between the simulated events and the actual galaxy distribution with that between the observed events and the actual galaxy distribution. Because of the flux limit, we cannot do so using the ORS galaxy sample. However, there is a galaxy survey with a limiting magnitude much deeper than that of the ORS, the Sloan Digital Sky Survey (SDSS; Stoughton et al. 2002). We conducted a study of the galaxy number density based on a comparison of the observed number counts between the ORS and the SDSS Early Data Release (Yoshiguchi et al. 2003a). As data obtained by the SDSS accumulate, we will be able to know the actual galaxy distribution of a much larger volume and make precise comparisons between numerical calculations and the observations.

In order to further investigate the relation between the number of the clustered events and the source distance, we calculate the number of events above $4 \times 10^{19}$ eV within $2.5^\circ$ from the direction of each source of Figure 3. The angle $2.5^\circ$ roughly corresponds to both the observational error of arrival directions and the deflection angle of UHECR when propagating in EGMFs ($B = 1$ nG) over $\sim 100$ Mpc. The result is shown in Figure 7. The solid angle of the observer viewed from distant sources is inversely proportional to the square of the distance. Thus, the contribution to cosmic-ray flux from a source closer to our Galaxy is larger than that from a distant source. This is reflected in Figure 7, where the event numbers in the direction of nearby sources are larger.

Fig. 6.—Correlation value between the simulated events above $4 \times 10^{19}$–$10^{20}$ eV and the source distribution of Fig. 3. The results are shown for the sources within 100, 200, and 300 Mpc from us. Error bars represent the statistical fluctuations due to the finite number of the simulated events.

Fig. 7.—Number of events within $2.5^\circ$ of the directions of UHECR sources in Fig. 3 as a function of the source distance. Error bars represent the statistical error due to the finite number of simulated events.
than those for distant sources. A source at \( \sim 280 \) Mpc that has a larger number of events in its direction happens to be located in the direction of a closer source.

We again note that the event number 100 corresponds to the one observed by the AGASA experiment. From Figure 7, there must be a source in the direction of triplet event sets within 100 Mpc from us at the 2 \( \sigma \) confidence level. This implies that the triplet observed by the AGASA would originate from sources within 100 Mpc. Indeed, Smialkowski et al. (2002) show that there is a merger galaxy, Arp 299 (NGC 3690 + IC 694), in the direction of the AGASA triplet at \( \sim 70 \) Mpc. Considering the analysis presented here, Arp 299 is the best candidate for the UHECR source.

Increasing the event number decreases the statistical uncertainty, as is evident from Figure 7, and thus the relation between the source distance and the number of clustered events in its direction becomes clear. As data accumulate from future experiments, we can know the distance of the source that contributes to a clustered event set by using this relation. Performing this procedure for all the event clusterings, we would be able to determine the distribution of UHECR sources within about 100 Mpc.

3.3. **Arrival Distribution of UHECRs above** \( 10^{20} \) eV

In this subsection, we present the results of the arrival distribution of UHECRs above \( 10^{20} \) eV. It is noted that our source model predicts the cosmic-ray spectrum with the GZK cutoff, unless other components are introduced at this energy range. Accordingly, the features of arrival distributions that we present here are expected to be observed by future experiments if the current HiRes spectrum is correct. If the AGASA spectrum is correct, UHECRs of top-down origin may dominate the cosmic-ray flux at this energy range. However, we may be able to separate UHECRs of bottom-up origin from those of top-down origin by using the feature of arrival distribution of bottom-up UHECRs, as discussed in § 4.

In Figure 8, we show the arrival distribution of UHECRs above \( 10^{20} \) eV predicted by the source model in Figure 3. This figure is same as Figure 3, but only the events with energies above \( 10^{20} \) eV are shown. Comparing with Figure 3, we find that the arrival directions are concentrated in a few directions. This can be also seen from Figure 9, which is the same as Figure 5, but for only UHECRs above \( 10^{20} \) eV. At \( \theta > 4^\circ \), the values of \( N(\theta) \) are almost equal to 0. This is because the sources of UHECRs above \( 10^{20} \) eV must be located in a limited volume of radius, at most \( \sim 100 \) Mpc, because of the pion production. Sources at larger distances cannot contribute to the cosmic-ray spectrum above this energy.

This feature of the correlation between the events and the sources can also be understood from the bottom panel of Figure 6. Note that the horizontal axis of this figure is the event number above \( 4 \times 10^{19} \) eV. Since the number of events above \( 10^{20} \) eV is very small, the statistical error is larger for \( E_{\text{th}} = 10^{20} \) eV than for \( E_{\text{th}} = 4 \times 10^{19} \) eV. From this figure, it is clear that the correlation with the sources within 100 Mpc is stronger for \( E_{\text{th}} = 10^{20} \) eV than that for \( E_{\text{th}} = 4 \times 10^{19} \) eV. On the other hand, this dependence becomes the opposite in the case of the sources within 200
and 300 Mpc, because UHECRs below $10^{20}$ eV can come from a much larger volume ($\sim$1 Gpc$^3$).

We also calculated the harmonic amplitude and the number of events within $2.5'$ from the directions of the sources for UHECRs above $10^{20}$ eV. The volume from which UHECRs at these energies can originate is much smaller than that for $E < 10^{20}$ eV. Although the dependence of the harmonic amplitude on random selection of UHECR sources from the ORS sample is relatively large for this reason, significant anisotropy on large angle scales may be observed when future experiments detect about several tens of cosmic rays above $10^{20}$ eV. The dependence of the number of events above $10^{20}$ eV within $2.5'$ from the directions of the sources on their distances is almost the same as that for events above $4 \times 10^{19}$ eV.

4. SUMMARY AND DISCUSSION

In this paper, we predicted the arrival distribution of UHECRs above $4 \times 10^{19}$ eV with the total number of events expected from next-generation experiments in the next few years. We performed event simulations using the ORS galaxy sample to construct a source model of UHECRs that can explain the current AGASA observations below $10^{20}$ eV (Paper I). It is noted that our prediction is not the exact arrival directions of each UHECR but the statistical features of the arrival distribution, because there are degrees of freedom in randomly selecting the UHECR sources from the ORS sample, and because this sample does not contain galaxies outside 107 Mpc ($\approx 80 h^{-1}$ Mpc). However, we will be able to know the actual galaxy distribution of a much larger volume by using the SDSS galaxy sample (Stoughton et al. 2002) with an increasing amount of data.

First, we calculated the harmonic amplitude and the two-point correlation function for the simulated event sets. We found that significant anisotropy on large angle scales will be observed when $\sim 10^5$ cosmic rays above $4 \times 10^{19}$ eV are detected by future experiments. The Auger array will detect cosmic rays with this event number in a few years of operation. The local enhancement model of UHECR sources (Isola & Sigl 2002; Sigl et al. 2003) predicts large-scale anisotropy of UHECR arrival distribution that reflects the spatial structure of the LSC, which cannot be seen from our model prediction (see Fig. 3). Thus, we will be able to determine which model is favored by the observations in a few years. The statistics of the two-point correlation function will also increase, and the angle scale at which there is strong correlation between the events corresponds to deflection angle of UHECRs propagating in the EGMF. Thus, it is expected that we will be able to know the strength of the EGMF, using the two-point correlation function for the observed arrival distribution of UHECRs, if our source and magnetic field models are supported by the future experiments.

Next, we investigated the relation between the number of clustered events and the distance of the sources in their direction. We found that the C2 triplet observed by AGASA (Hayashida et al. 2000) may originate from a source within 100 Mpc from us. Indeed, Smialkowski et al. (2002) show that there is a merger galaxy, Arp 299 (NGC 3690 + IC 694), in the direction of the AGASA triplet at $\sim$70 Mpc. Considering the analysis presented here, Arp 299 is the best candidate for the UHECR source.

When the event number increases, the statistical uncertainty decreases, as is evident from Figure 7, and thus the relation between the source distance and the number of clustered events in its direction becomes clear. Using this relation, we will be able to determine the distribution of UHECR sources within about 100 Mpc.

Identification of the sources of UHECRs is extremely important. At first, this will provide some kinds of information about poorly known parameters that influence the propagation of UHECRs, such as extragalactic and Galactic magnetic fields and the chemical composition of observed cosmic rays. Furthermore, this will give invaluable information on mechanisms and physical conditions that lead to acceleration of cosmic rays to energies of the order of $10^{20}$ eV. In particular, we showed that there was strong correlation between the arrival distribution of UHECRs above $10^{20}$ eV and the source distribution within 100 Mpc. If the cosmic-ray spectrum measured by the HiRes experiment is correct, an UHECR arrival distribution similar to that in Figure 8 will be observed by future experiments. We will be able to know the maximum energies achieved by cosmic rays in each identified object. If the AGASA spectrum is correct, cosmic-ray flux is dominated by the component of top-down origin. However, the number density of the supermassive particles, whose decay product can be observed in UHECRs above $10^{20}$ eV, is estimated as $10^{36}$ Mpc$^{-3}$ in our Galactic halo in order to explain the observed flux, as we discussed in Paper I. In this case, there would be no small-scale anisotropy of arrival distribution of UHECRs above $10^{20}$ eV that are generated by top-down mechanisms. On the other hand, the arrival directions of bottom-up UHECRs are strongly concentrated in a few directions, as presented in § 3.3. We may be able to extract UHECRs of bottom-up origin from ones of top-down origin and obtain information on the maximum energies of cosmic rays.

In Paper I, we showed that the number density of UHECR sources may be $\sim 10^{-6}$ Mpc$^{-3}$ in order to explain the UHECR arrival distribution observed by the AGASA experiments. Nevertheless, we could not know which of the
astrophysical objects mainly contributes to the observed cosmic-ray flux. However, with the method of identifying the sources of UHECRs developed in this paper, we will reveal their origin and obtain useful information on acceleration mechanism to the highest energy.

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