SEARCH FOR CORRELATIONS OF THE ARRIVAL DIRECTIONS OF ULTRA-HIGH ENERGY COSMIC RAY WITH EXTRAGALACTIC OBJECTS AS OBSERVED BY THE TELESCOPE ARRAY EXPERIMENT

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ABSTRACT

We search for correlations between positions of extragalactic objects and arrival directions of Ultra-High Energy Cosmic Rays (UHECRs) with primary energy $E \geq 40$ EeV as observed by the surface detector array of the Telescope Array (TA) experiment during the first 40 months of operation. We examined several public astronomical object catalogs, including the Veron-Cetty and Veron catalog of active galactic nuclei. We counted the number of TA events correlated with objects in each catalog as a function of three parameters: the maximum angular separation between a TA event and an object, the minimum energy of the events, and the maximum redshift of the objects. We determine combinations of these parameters which maximize the correlations, and calculate the chance probabilities of having the same levels of correlations from an isotropic distribution of UHECR arrival directions. No statistically significant correlations are found when penalties for scanning over the above parameters and for searching in several catalogs are taken into account.

Subject headings: Astroparticle physics,cosmic rays, acceleration of particles

1. INTRODUCTION

Clarifying the origin of Ultra-High Energy Cosmic Rays (UHECRs) is one of the most important unsolved problems in modern astrophysics (e.g. Kotera & Olinto 2011). It is generally thought that cosmic rays with energies greater than 10^{18} eV (1 EeV) are of extragalactic origin because the Galactic magnetic fields are not strong enough to confine them. Indeed, no apparent anisotropy in arrival directions of UHECRs along the Galactic plane has been found. On the other hand, a steepening in the energy spectrum of UHECRs at around 50 EeV is observed by the High Resolution Fly's Eye (HiRes) experiment and the Telescope Array (TA) experiment (Abbasi et al. 2008b; Abu-Zayyad et al. 2012b), and also by the Pierre Auger Observatory in a similar energy region (Abraham et al. 2008, 2010). This can be explained as a consequence of the cosmic ray energy losses due to interactions with the Cosmic Microwave Background (CMB), as predicted by (Greisen 1966), and (Zatsepin & Kuz'min 1966).

In this case, we expect that most of the observed cosmic rays of the highest energies originate from sources within the GZK horizon ($\sim$100 Mpc), and a correlation between nearby objects and arrival directions of cosmic rays is expected. The UHECRs are deflected by the Galactic and extragalactic magnetic fields on their way to Earth. The deflection angles are determined by the particle charges, source distances, and strength of the magnetic fields. For example, in case of a proton arriving from a 100 Mpc distance through a random extragalactic magnetic field 1 nG and correlation length of $\sim$1 Mpc, the expected deflection angle is $3 - 5°$ for 100 EeV (and less than $15°$ for 40 EeV) using the existing magnetic field estimates (Han et al. 2006; Sun et al. 2008; Pshirkov et al. 2011; Kronberg 1994).

The TA experiment observes UHECRs in the northern hemisphere using a Surface Detector (SD) array (Abu-Zayyad et al. 2012c) of $\sim 700\,\mathrm{km}^2$ area located in Millard County, Utah, USA (39.3° N, 112.9° W). Three Fluorescence Detector (FD) stations (Tokuno et al.

2012; Matthews et al. 2007) surround the SD array (Kawai et al. 2008) and view the atmosphere above it. The SD array consists of 507 SDs installed on a square grid with 1.2 km spacing, and measures particles from Extensive Air Showers (EASs) at ground level. The energy and the arrival direction of a primary particle are determined from observed energy deposits as a function of distance from the shower core in the SDs and the arrival time distribution of the EAS particles. The test operation of the SD array began in March 2008, and the full SD array has been operational with a uniform trigger criteria from May 11, 2008. The present analysis uses only the events detected by the SD array because this data set has the greatest statistics than that by the FDs.

Assuming the sources have the same intrinsic UHECR luminosities, the arrival directions of higher energy cosmic rays from nearby sources are expected to correlate better with the source positions. We search for the correlations between the TA events and objects in catalogs by changing three parameters: the minimum energy of the cosmic ray events, $E_{\rm min}$, the separation angle, ψ, between the cosmic ray arrival direction and the object, and the maximum redshift, $z_{\rm max}$, of the objects. A similar approach has been taken in the analyses by the Pierre Auger Observatory (Abreu et al. 2007, 2008, 2010) and by the HiRes experiment (Abbasi et al. 2008a) using the VCV catalog of 12th edition (Veron-Cetty & Veron 2006).

As putative sources of UHECR, we examine the objects in the 13th edition of the VCV catalog (Veron-Cetty & Veron 2010). This catalog is a compilation of several surveys made under different conditions such as Field Of Views (FOVs), observation periods, etc. It does not represent a homogeneous sample of Active Galactic Nuclei (AGNs), and its degree of completeness is unknown (Veron-Cetty & Veron 2010). In addition, we have investigated unbiased data sets from different measurements, namely, radio: the third Cambridge catalog of radio sources catalog (3CRR) (Laing, Riley & Longair

1983), infrared: the 2MASS (the Two Micron All-Sky Survey) redshift survey catalog (2MRS) (Huchra et al. 2012), X-Ray: Swift BAT (Burst Alert Telescope) 58-Month hard X-ray survey catalog (SB-58M) (Baumgartner et al. 2010) and 60-Month AGN survey catalog (SB-AGN) (Ajello et al. 2012), and Gamma-ray: 2nd Fermi large area telescope AGN catalog (2LAC) (Ackermann et al. 2011). In each catalog, we select only those objects that have redshift information. In the case of the 2LAC catalog, this criterion reduces the number of objects by $\sim$50%.

The paper is organized as follows. The observation status of the SD array and qualities of reconstructed events are briefly described in Section 2. The details of the parameter scanning in the correlation searches using the object catalogs are given in Section 3, and the results are described in Section 4. We also investigated penalties for the multi-catalog scanning in Section 5. The conclusions from this analysis are in Section 6.

2. SD DATA

In this work we use the SD air shower events observed in the first 40-month run of TA from May 2008 through September 2011. These events are triggered by a three-fold coincidence of adjacent SDs within 8μs (Abu-Zayyad et al. 2012c).

The details of SD event reconstruction are described elsewhere (Ivanov et al. 2012; Abu-Zayyad et al. 2012b). First, the shower geometry including the arrival direction is obtained using the time differences between the observed signals at each SD. Next, the precise shower geometry and the lateral distribution of shower particles are determined using the observed energy deposit in each SD. Finally, the primary energy is determined from the lateral distribution. The overall energy scale of the SD events is fixed by calibration with the FD energy scale using a hybrid event set as described in the reference (Abu-Zayyad et al.

2011). The systematic uncertainty in energy determination is 22%.

The data quality cuts for the reconstructed events are the same as in the previous TA analysis papers (Abu-Zayyad et al. 2012a,b). The events are cut if the zenith angle is greater than 45° and/or the core position is within 1200 m of the SD array boundary. The EAS reconstruction efficiency under these criteria is greater than 98% including the duty cycle of the SD array for $E > 10$ EeV (Abu-Zayyad et al. 2012b,c). The accuracy in arrival direction determination is 1.5° and the energy resolution is better than 20% in this energy range.

The number of events remaining after reconstruction and quality cuts is 988 for $E \geq 10$ EeV, 57 for $E \geq 40$ EeV, and 3 for $E \geq 100$ EeV. From our Monte-Carlo studies including the full detector response simulations, we confirmed that the acceptance of the SD array is fully geometrical, i.e., independent of the arrival direction up to $\theta = 45°$ for showers with energies greater than 10 EeV (Abu-Zayyad et al. 2012a,b,c). We also confirmed that the arrival direction distribution of the observed events in the horizontal coordinates and the equatorial coordinates are consistent with large scale isotropy shown in Figure 1. In this analysis, we use the geometrical acceptance to generate random events for reasons of computational efficiency. The total exposure of the SD array in the first 40 months of operation is 3.1×10^3 km^2 sr yr including the quality cuts.

3. CORRELATION ANALYSIS

3.1. OBJECT CATALOGS

We use the catalogs of extragalactic objects resulting from measurements as listed in Table 2. In several catalogs, the objects near the Galactic plane are excluded to avoid incompleteness from the experimental limitation by the authors of each catalog. We also exclude the observed SD events in the corresponding regions.

The target objects and the cut criteria in the each catalog are summarized below. These criteria (e.g. significance level) were chosen by the authors of the each catalog. The 3CRR catalog contains radio galaxies detected at 178 MHz with fluxes greater than 10 Jy (Laing, Riley & Longair 1983). Objects in the direction of the Galactic disk ($|b| < 10^\circ$) were not included. The 2MRS (Huchra et al. 2012) catalog is derived from the 2MASS observation with detection range between $1 - 2$ μm and $K_s \leq 11.75$ magnitude. This catalog also loses completeness near the Galactic plane, so the authors of the catalog excluded regions with $|b| < 5^\circ$ for $30^\circ \leq l \leq 330^\circ$ and $|b| < 8^\circ$ otherwise. The SB-58M catalog consists of objects which were detected with a significance greater than 4.8σ in the energy range of $14 - 195$ keV in the first 58 months of observation by Swift BAT. We select the extragalactic objects in this catalog for this work. The catalog of SB-AGN contains AGNs with at least 5σ significance in the energy range of $15 - 55$ keV in the first 60 months of observation by Swift BAT. The 2LAC (Ackermann et al. 2011) data set consists of AGNs detected with at least 4σ significance in the energy range of 100 MeV$-$100 GeV in the first 24 months of observation by Fermi-LAT. The region of the Galactic disk $|b| < 10^\circ$ is cut away. We also examine the VCV catalog which is a compilation of several AGN surveys. The number of objects and the SD events after the cuts applied in each case are given in Table 3.

3.2. METHODS

For a given set of parameters $(E_{\rm min}, \psi, z_{\rm max})$, there are N events with energies $E \geq E_{\rm min}$. We can count the number of events, k, out of N which are correlated with objects in a catalog with redshifts $z \leq z_{\rm max}$ and within the angular separation ψ. We can calculate the chance probability, P, that k or more correlated events are found from an isotropic UHECR flux under the same conditions. We carry out a parameter scan in $(E_{\rm min}, \psi, z_{\rm max})$ space to find the set of parameters which maximizes the correlation between the TA events and the catalog objects, i.e., minimizes P. To determine the probability, P, we first obtain the probability, p, that a random event is correlated with at least one object by chance for a given $(\psi, z_{\rm max})$. We generate 10^4 random events to obtain the probability, p, in the same experimental region of the each catalog.

Then P can be obtained as a cumulative binomial probability:

$$P = \sum_{j=k}^{N} C_j^N p^j (1-p)^{N-j}. \quad (1)$$

The scan over parameters was performed as follows. The value of $E_{\rm min}$ is set by the energy of the N-th highest energy event. We scan over all values of N such that $E_{\rm min}$ is greater than 40 EeV. Note that this energy is less than the energy (50 EeV) at which the TA energy spectrum begins to fall off steeply (Abu-Zayyad et al. 2012b). We set the upper boundary of the parameter $z_{\rm max}$ as 0.03, which corresponds to the distances smaller than 120 Mpc. This is comparable to the GZK horizon. The selected step size of $z_{\rm max}$ is 0.001, which is the typical accuracy in the redshift measurements. The separation angle, ψ, is varied from 1° to 15°. The maximum search window of $\psi = 15^\circ$ is selected as appropriate for lower energy events ($\sim$40 EeV) arriving from the distance of 100 Mpc. The selected step size in ψ is chosen as 0.1° for $\psi < 8^\circ$ and 1° for $8^\circ \leq \psi \leq 15^\circ$. The parameter ranges and step sizes are summarized in Table 1.

The minimum P obtained from this procedure does not represent the correlation probability directly, because the parameter scanning enhances the correlation probability artificially (Tinyakov & Tkachev 2004). Therefore, a penalty for parameter scanning should be evaluated and the true probability of correlation must include this penalty. This will be described in Section 4.

4. RESULTS

4.1. RESULTS OF THE PARAMETER SCAN ANALYSIS

The results of the parameter scan are listed in Table 4. The smallest value of $P_{\rm min}^{\rm obs}$ among all the catalogs is 1.3×10^{-5} found in the SB-AGN catalog with the best parameters $(E_{\rm min}, \psi, z_{\rm max})_{\rm best} = (62.20~{\rm EeV}, 10^\circ, 0.020)$. A sky map of the TA events and the objects under the condition $(E_{\rm min}, \psi, z_{\rm max})_{\rm best}$ which gives the smallest $P_{\rm min}^{\rm obs}$ is shown in Figure 2. All the observed UHECRs with $E \geq E_{\rm min}$ correlate with at least one object with $z \leq z_{\rm max}$ in the SB-AGN catalog. Figure 3, and 4 show the probability as a function of each parameter $(E_{\rm min}, \psi, z_{\rm max})_{\rm best}$ while fixing the values of the other two at the optimum value for this data comparison.

Now let us consider the penalty for the parameter scanning. We evaluate the probability, $P_{\rm PPS}$, of finding a correlation by chance with $P_{\rm min}^{\rm sim}$ smaller than that obtained from the data as follows (for a more detailed description of the penalty calculation see, e.g., Tinyakov & Tkachev 2004). We generate 10^4 random sets of N "cosmic ray events", where N is the same as the number of the observed events with energies greater than 40 EeV. For each of the mock event sets, the parameter scanning was carried out using exactly same method as for the observed data set, and $P_{\rm min}^{\rm sim}$ was calculated. Note that the parameters $(E_{\rm min}, \psi, z_{\rm max})_{\rm best}$ which yield $P_{\rm min}^{\rm sim}$ are different for each of the 10^4 trials. The distribution of $P_{\rm min}^{\rm sim}$ in case of the SB-AGN catalog is shown in Figure 5 together with $P_{\rm min}^{\rm obs}$. One can see that rather small values $P_{\rm min} \leq 1.3\times10^{-5}$ can happen even though the simulated UHECR distribution is isotropic.

If we repeat the same experiment and the parameter scanning many times, the value of our result $P_{\rm min}^{\rm obs} = 1.3\times10^{-5}$ could be just a chance occurrence. The probability including the Penalty for the Parameter Scanning (PPS) is evaluated as $P_{\rm PPS} = 0.01$ for the SB-AGN catalog, and the values for all the catalogs are listed in Table 4. The smallest value of $P_{\rm PPS}$ among the catalogs is 0.01 from the the SB-AGN catalog. This does not yet include the penalty for searching in several catalogs.

If we have several catalogs, regardless of whether they are independent or partially overlapping, there is a possibility of finding a catalog which gives the same or smaller $P_{\rm min}^{\rm obs}$ value by chance, even though there are no correlations between the events and the objects. The straightforward way to calculate the penalty factor associated with the partially overlapping catalogs, as is the case in our analysis, is to include all the catalogs in the Monte-Carlo simulation. Therefore, we have repeated the simulation with 10^4 mock sets as described above, but with the scanning performed in all six catalogs. Calculating the fraction of mock sets that show equal or better correlation than the data, we find that the final probability with a Penalty of Parameter Scanning (PPS) and a Penalty of multi-Catalog Scanning (PCS) $P_{\rm PPS+PCS} = 0.09$. Therefore, we conclude that no significant correlation between UHECRs and the astronomical objects is found in the current TA data set.

4.2. UNCERTAINTIES

First, we consider the effect of finite resolution in the scanning parameters. The uncertainty in determination of the arrival directions and energy only make correlations worse due to direction smearing and the contamination of the lower energy events than $E_{\rm min}$. Therefore, the obtained $P_{\rm min}^{\rm obs}$ already includes these resolution effects. The same concerns the uncertainty in the redshifts of the catalog objects.

Consider now the effect of the systematic uncertainty in energy determination. As mentioned above, this uncertainty is 22% (Abu-Zayyad et al. 2011). Note, however, that the present analysis with the parameter scanning is independent of absolute energy scale: the *energies* of the events are no more than keys for event sorting, and a systematic energy shift does not affect the scanning in $E_{\rm min}$, hence the number of events involved in the correlation with the objects and the probability $P_{\rm min}^{\rm obs}$.

The last issue to discuss is the incompleteness of the catalogs, which remains even after we cut out the regions around the Galactic plane. The objects in the VCV catalog are inhomogeneous because it is a mere compilation of objects detected under different conditions. The completeness of the other catalogs, in particular the 2LAC, could be affected by our cuts, particularly by the selection of objects with the known redshift. While the incompleteness may make the *interpretation* of correlations ambiguous if they are present, it does not affect the calculation of $P_{\rm min}^{\rm obs}$. In fact, the effect of the incompleteness cancels out in $P_{\rm min}^{\rm obs}$ since the same set of objects is used to cross-correlate with the data and each mock event set. Therefore, the incompleteness of the catalogs cannot produce spurious correlations (although it may, in principle, be responsible for their absence).

5. DISCUSSION

5.1. SEARCH FOR CORRELATIONS WITH A SPECIFIC TYPE OF OBJECT

So far we have treated the objects in each catalog equally regardless of their class. Now let us examine whether there is a specific type of object that has stronger correlations with UHECRs than others. We will consider the case of the SB-AGN catalog which shows strongest correlations with UHECRs.

First, we count the number of objects of each class in the TA FOV with redshifts smaller than 0.02. Some of the objects are labeled “unclassified” in the catalog. For these we used the information from other surveys (Noguchi et al. 2010; Parisi 2011; Veron-Cetty & Veron 2010; Baumgartner et al. 2010). The fractions of Seyfert 2, 1, 1.5, 1.9 and LINER galaxies in the SB-AGN catalog satisfying the above conditions are 0.441, 0.235, 0.132, 0.044, and 0.044, respectively (the total fraction of other class AGNs: 0.044, and the fraction of the unclassified AGN: 0.059). The total number of AGNs which are correlated with UHECRs is 22 with the parameters in Table 4 (note that the number of UHECR events and that of AGNs are not the same because some of the events fall within the given angular distance from several sources). Among these 22 AGNs the fractions of Seyfert 2, 1, 1.5, 1.9, LINER, and unclassified galaxies are 0.455, 0.182, 0.227, 0.045, 0.045, and 0.045, respectively. We see that the largest difference is for the Seyfert 1.5 galaxies. The probability, P, of finding 5 or more correlated Seyfert 1.5 galaxies out of 22 by chance can be evaluated by the cumulative binomial probability with an expectation of 0.13, and is $P = 0.16$. Therefore, no significant correlation with a specific type of AGN in the SB-AGN catalog is found.

6. CONCLUSION

We examine the correlations between the observed UHECR arrival directions and the extragalactic objects from the different survey catalogs under assumption that the sources have the same intrinsic UHECR luminosities. We use the TA-SD events with energies greater than 40 EeV obtained in the first 40 months of observation. We search for maximum correlations by scanning over three parameters $E_{\rm min}$, ψ, and $z_{\rm max}$ in six different catalogs. The smallest chance probability among these six catalogs was found with the Swift BAT (60-month) AGN catalog, $P^{\rm obs}_{\rm min} = 1.3 \times 10^{-5}$. This probability increases to $P_{\rm PPS} = 0.01$ when we include the penalty for the three-parameter scanning in the Swift BAT catalog alone, and to $P_{\rm PPS+PCS} = 0.09$ when scanning in all the catalogs is taken into account. Therefore, we conclude that no significant correlation with the considered catalogs of extragalactic objects is found in the present TA data set. Investigating specifically the case of the Swift BAT (60-month) AGN catalog which gives the strongest correlation, we find that no particular subclass of objects is responsible for this correlation.

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Parameter	Range	Step size
Energy (EeV)	$E \geq 40$	Energy of each event by sorted order
Redshift (z)	$0.001 \leq z \leq 0.030$	0.001
Window (degree)	$1 \leq \psi < 8$	0.1
	$8 \leq \psi \leq 15$	1

Table 1: List of the scan regions and step size for each scan parameter.

Catalog	Range	N_{all}	N_{target}
3CRR	compilation of Radio surveys	173	16
2MRS	IR (1−2μm)	43533	13547
SB-58M	X-ray (14 − 195 keV)	1092	161
SB-AGN	X-ray (15 − 55 keV)	428	102
2LAC	γ-ray (100 MeV−100 GeV)	1126	6
VCV	compilation of AGNs	168941	762

Table 2: List of the configuration of the used catalogs. $\mathrm{N_{all}}$: number of all objects contained within the catalog, $\mathrm{N_{target}}$: number of objects with the redshift $z < 0.03$ within the TA FOV.

Catalog	Cut region (degree)	N ($E \geq$40 EeV)
3CRR	$\lvert b \rvert$ <10°, δ <10°	41
2MRS	$\lvert b \rvert$ <5° for 30° $\leq l \leq$ 330° $\lvert b \rvert$ <8° otherwise	56
SB-58M	None	57
SB-AGN	None	57
2LAC	$\lvert b \rvert$ <10°	49
VCV	None	57

Table 3: List of the cut region away from the Galactic plane of the each catalog and the number (N) of events remaining (the maximum number is 57). Symbols mean: b: Galactic latitude, l: Galactic longitude, δ: declination of the equatorial coordinate.

Catalog	$E_{\rm min}$ (EeV)	ψ (degree)	$z_{\rm max}$ (z)	A	N	k	p	$P_{\rm min}$	$P_{\rm PPS}$
3CRR	66.77	2.0	0.017	4	11	1	0.0020	2.2×10^{-2}	0.75
2MRS	51.85	6.5	0.005	660	31	29	0.62	8.5×10^{-5}	0.21
SB-58M	57.46	11	0.017	79	25	25	0.68	6.1×10^{-5}	0.04
SB-AGN	62.20	10	0.020	58	17	17	0.52	1.3×10^{-5}	0.01
2LAC	55.41	12	0.018	3	23	3	0.069	2.1×10^{-1}	0.83
VCV	62.20	2.1	0.016	288	17	8	0.14	8.6×10^{-4}	0.25

Table 4: Summary of correlations with the best parameter set (minimum threshold, Window size, maximum redshift) for each catalog. A: number of objects with the redshift $\leq z_{\rm max}$, N: number of observed cosmic ray events with the energy $E \geq E_{\rm min}$, k: number of events correlated with objects, p: probability of correlation for a single event from an isotropic distribution, $P_{\rm min}$: the cumulative binomial probability to obtain k or more estimated from an isotropic distribution, $P_{\rm PPS}$: the probability after including the penalties from parameter scanning.

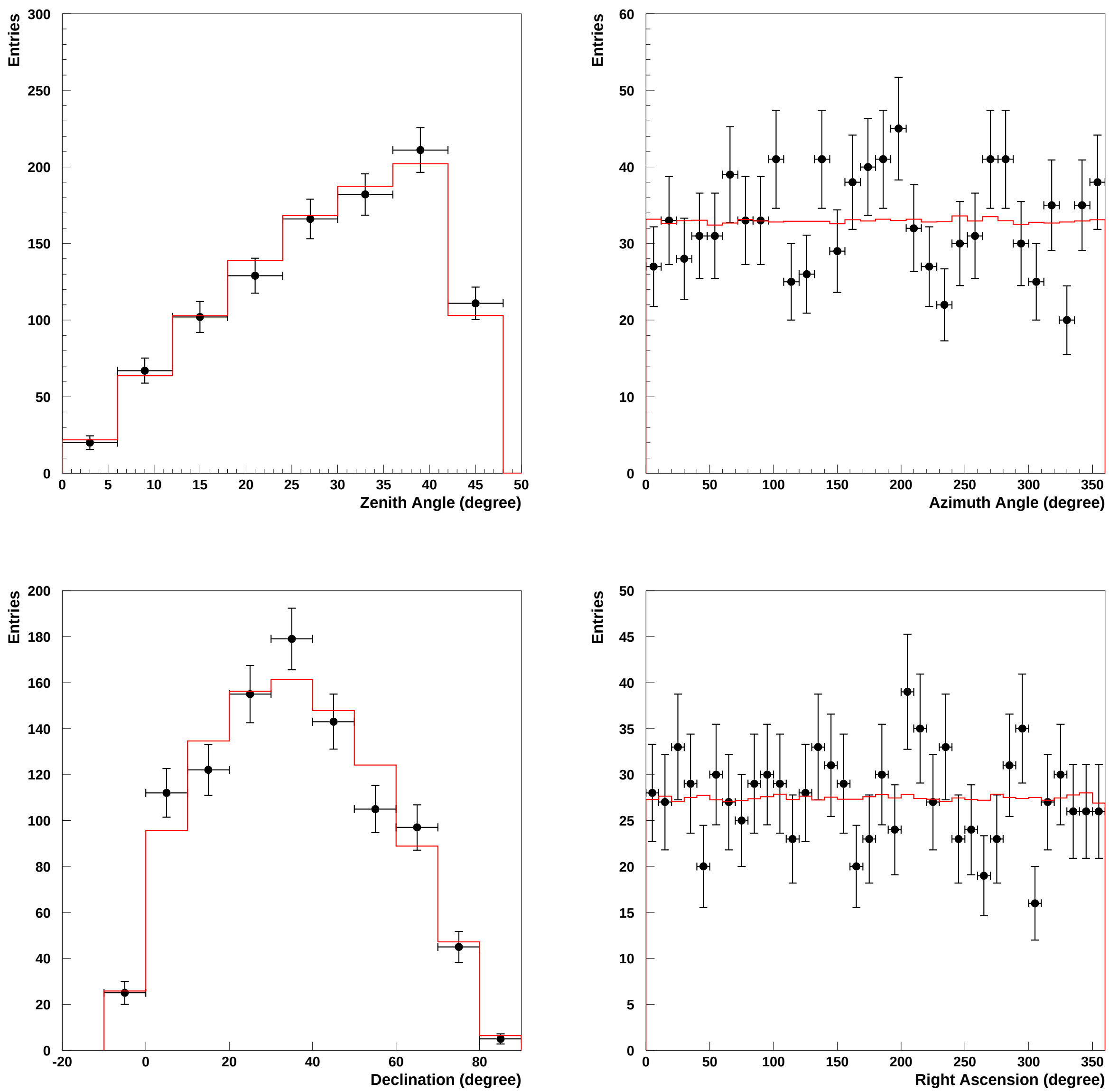

Fig. 1.— The distribution of observed data (plot) and the simulated data with the geometrical acceptance (histgram) with the energy > 10 EeV. The top left: zenith angle, the top right: azimuth angle, the bottom left: declination, and the bottom right: right accension.

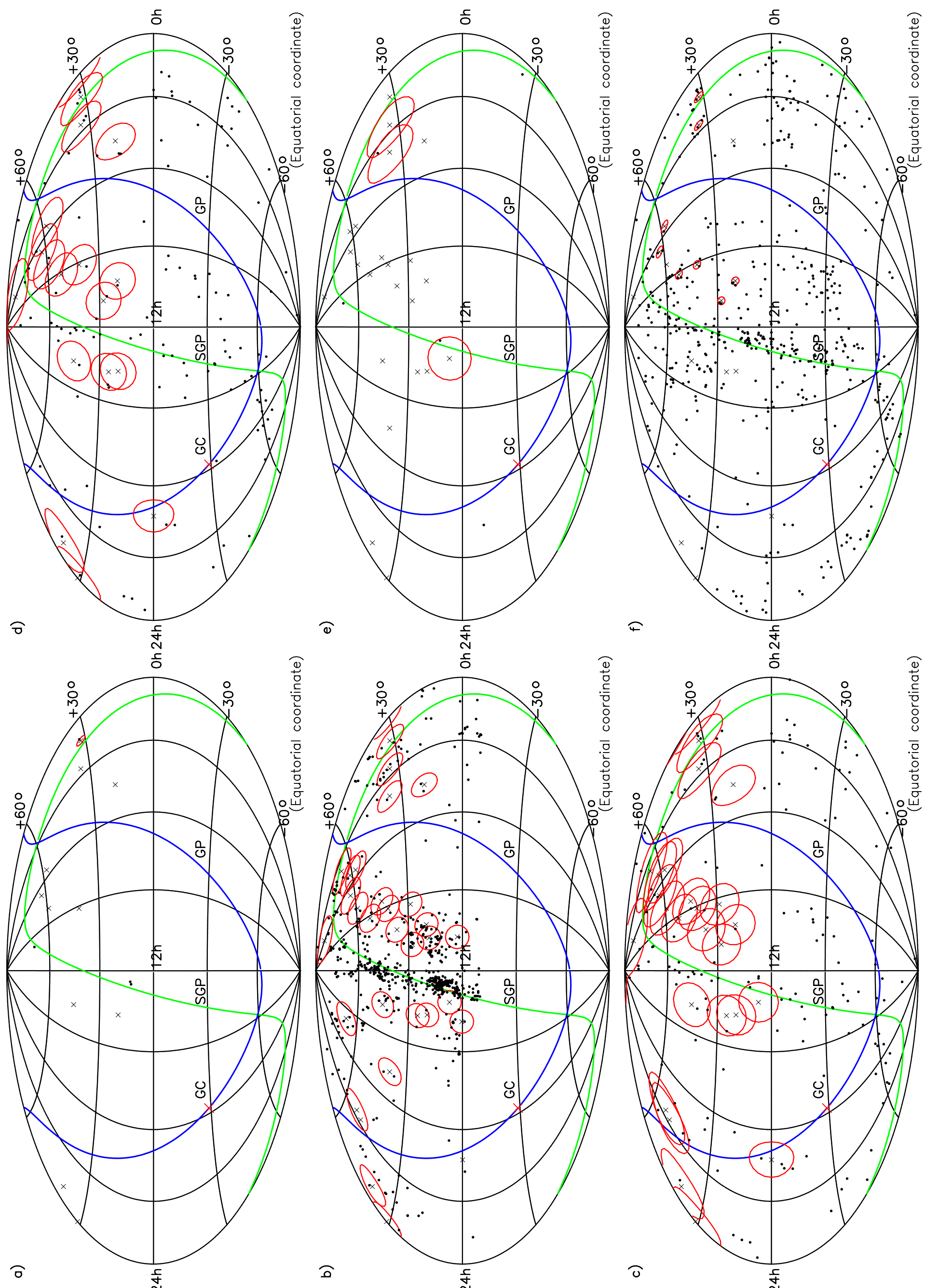

Fig. 2.— Arrival directions of observed UHECR with the objects of the each catalog (a: 3CRR, b: 2MRS, c: SB-58M, d: SB-AGN, e: 2LAC, and f: VCV). Dots: catalog objects, x: arrival direction of observed cosmic rays, Circle: window around cosmic ray events, GC: Galactic Center, GP: Galactic Plane, SGP: Super Galactic Plane.

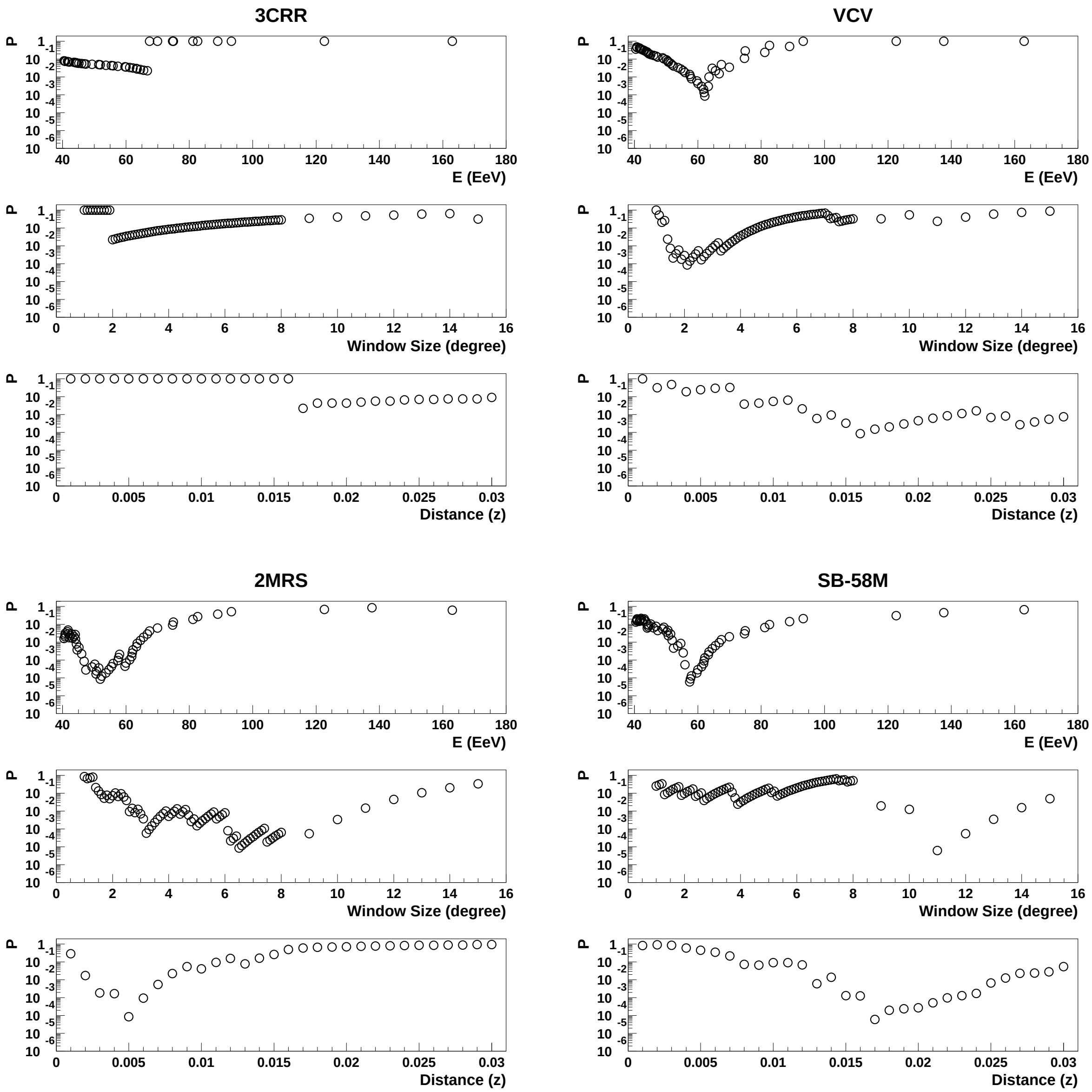

Fig. 3.— Cumulative binomial probability distribution for the 3CRR (top left panel), VCV catalog (top right panel), 2MRS (bottom left panel), and SB-58M (bottom right panel). Each panel shows the probability distribution with Energy threshold ($E_{\min}$) of observed cosmic rays (top), window ψ (middle), redshift $z_{\max}$ (bottom). In the each plot, the other two parameters are fixed at which parameter set provides $P_{\min}$.

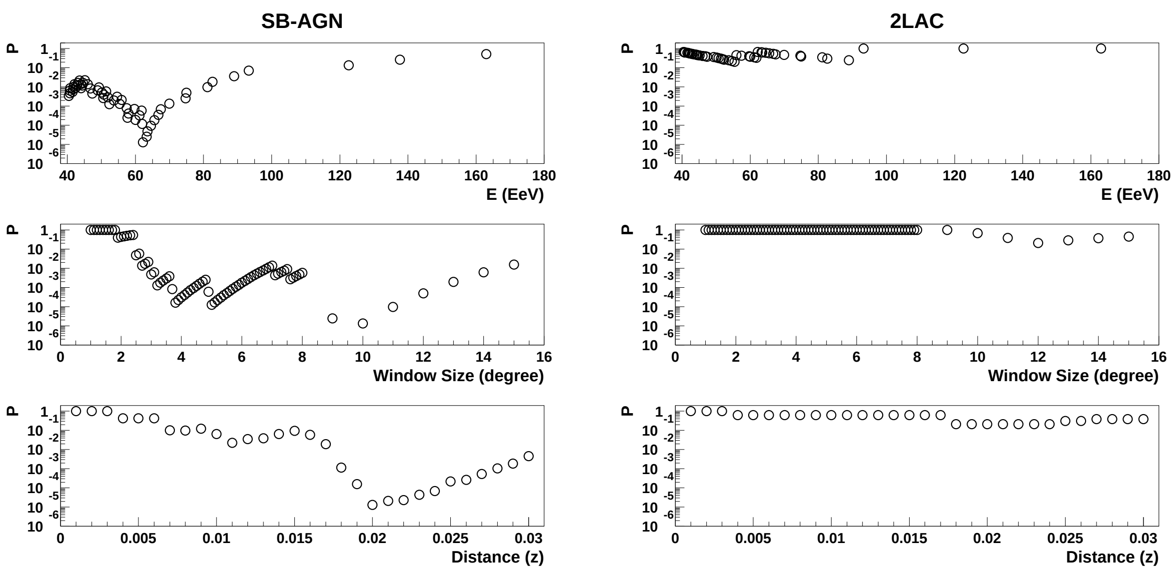

Fig. 4.— Cumulative binomial probability distribution for the SB-AGN (left panel), 2LAC (right panel). Each panel shows the probability distribution with Energy threshold ($E_{\rm min}$) of observed cosmic rays (top), window ψ (middle), redshift $z_{\rm max}$ (bottom). In the each plot, the other two parameters are fixed at the optimum value.

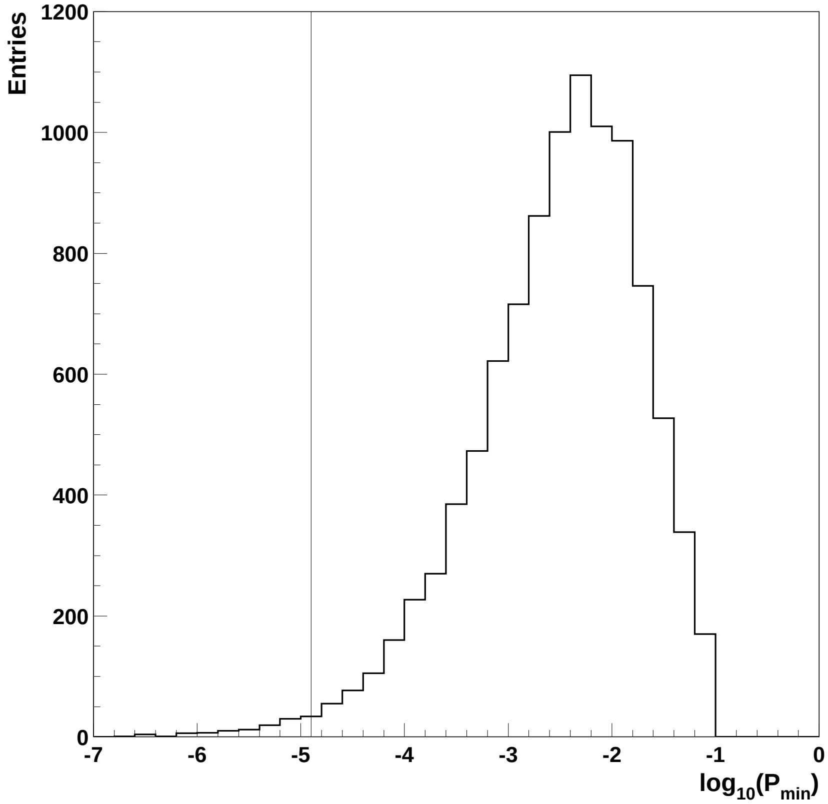

Fig. 5.— Distribution of probability $P_{\rm min}^{\rm sim}$ for SB-AGN catalog determined from 10^4 simulated isotropic data sets. The observed $P_{\rm min}^{\rm obs} = 1.3 \times 10^{-5}$ is shown as a vertical line.