33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE

ICRC 2013

Search for correlations of the arrival directions of ultra-high energy cosmic ray observed by the Telescope Array experiment with extragalactic objects

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Abstract: We searched for corrlations between directions of extragalactic objects and arrival directions of ultra-high energy cosmic rays observed by the surface detector array of the Telescope Array experiment for the first 40 Months. Several public object catalogs from different wavelength surveys, and the Veron-Cetty and Veron catalog of active galactic nuclei were examined. We searched for the maximum correlation with changing three parameters: the maximum anguar separation of a TA event and an object, the minimum energy of the events, and the maximum redshift of the objects. We determined combinations of these parameters which maximize the correlations, and calculated the chance probabilities of having same levels of correlations from an assumption of isotropic distribution of UHECR arrival directions. No statistically significant correlations were found when penalties for scanning over the above parameters and for searching in several catalogs are taken into account.

Keywords: ultra-high energy cosmic rays, extragalactic objects, correlation study

1 Introduction

Clarifying the origin of ultra-high energy cosmic rays (UHECRs) is one of the most important unsolved problems in modern astrophysics. It is generally thought that cosmic rays with energies greater than 10^{18} eV (1 EeV) are of extra-galactic 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 [1, 2], and also by the Pierre Auger Observatory in a similar energy region [3, 4]. This steepening can be explained as a consequence of the cosmic ray energy losses due to interactions with the cosmic microwave background (CMB), as predicted by [5, 6].

From these scenarios, the sources of cosmic rays of the highest energies are within the GZK horizon ($\sim$100 Mpc), and a correlation between nearby extragalactic objects and arrival directions of cosmic rays is expected. The UHECR 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, for protons arriving from 100 Mpc distance, the deflections in he extragalactic magnetic fields are expected to be negligible [7] compared to the deflection angle of $3-5^\circ$ for 100 EeV (less than 15° for 40 EeV) in the Galactic magnetic field models [8, 9, 10, 11].

The TA experiment observes UHECRs in the northern hemisphere using a surface detector (SD) array [12] of $\sim$ 700 km^2 located on Utah, USA (39.3° N, 112.9° W), and three fluorescence detector (FD) stations [13, 14] surrounding the SD array [15]. The SD array consists of 507 SDs deployed on a grid shape with 1.2 km spacing, and measures extensive air shower (EAS) particles at the ground level ($\sim$1400 m a.s.l.). The energy and the arrival direction of a primary particle are determined from observed energy deposits in the SDs and the arrival time distribution of the EAS particles. The full SD array has been operated from May 11, 2008. In this work we used only the events detected by the SD array because they have by far larger statistics and better angular resolution.

Assuming the sources have the same UHECR luminosities, the arrival directions of higher energy cosmic rays from nearby sources are expected to correlate better with the source positions. We searched 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 of objects, $z_{\rm max}$. A similar approach has been taken in the analyses by the Pierre Auger Observatory [16, 17, 18] using the VCV catalog of 12th edition [19].

We have investigated unbiased data sets of the extra galactic objects from the different wave length measure-

ments, radio: the third Cambridge catalog of radio sources catalog (3CRR) [20], infrared: the 2MASS (the Two Micron All-Sky Survey) redshift survey catalog (2MRS) [21], X-Ray: Swift BAT (Burst Alert Telescope) 58-Month hard X-ray survey catalog (SB-58M) [22] and 60-Month AGN survey catalog (SB-AGN) [23], and Gamma-ray: 2nd Fermi large area telescope AGN catalog (2LAC) [24]. We also have examined the objects in the 13th edition of the VCV catalog [25]. This catalog is a compilation of several surveys under different conditions such as FOVs, observation periods, etc. It does not represent a homogeneous sample of the Active Galactic Nuclei (AGN), and its degree of completeness is unknown [25]. In each catalog, we select objects that have redshift information. In the case of 2LAC catalog, this criterion reduces the number of objects by $\sim$50%.

2 SD Data

In this work we use the SD air shower events observed from May 2008, to September 2011. The details of the SD event reconstruction are described in the references [2, 26]. The data quality cuts for the reconstructed events are the same as in the previous TA analysis papers [2, 27]. The events are cut if the zenith angle is greater than 45°. The accuracy in arrival direction determination is 1.5° and the energy resolution is better than 20% for $E > 10$ EeV. The number of the reconstructed events after the normal quality cuts is 988 with $E \geq$10 EeV, 57 with $E \geq$40 EeV, and 3 with $E \geq 100$ EeV.

3 Correlation analysis

We count the number of events k out of N events ($E \geq E_{\rm th}$) which are correlated with objects in a catalog with redshifts $z \leq z_{\rm max}$ within the angular distance, 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 carried 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. To determine the probability P, we first obtained the probability p that an UHECR at a position randomly selected in the sky assuming isotropy is correlated with at least one object by chance for given $(\psi, z_{\rm max})$. 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 have scanned over all values of N such that $E_{\rm min}$ is greater than 40 EeV. We set the upper boundary of the parameter $z_{\rm max}$ as 0.03 ($\sim$120 Mpc), and the step of $z_{\rm max}$ as 0.001. The separation angle, ψ, was varied from 1° to 15°. The step in ψ is chosen as 0.1° for $\psi < 8°$ and 1° otherwise.

The minimum P obtained from this procedure does not represent the correlation probability directly, because the parameter scanning enhances the correlation probability artificially [28]. Therefore, a penalty for the parameter scanning should be evaluated, and the true probability of correlation must include this penalty.

Catalog	Range
3CRR	Radio (178 MHz)
2MRS	IR ($1-2\mu$m)
SB-58M	X-ray ($14-195$ keV)
SB-AGN	X-ray ($15-55$ keV)
2LAC	γ-ray (100 MeV$-$100 GeV)
VCV	combined

Table 1: List of the configuration of the used catalogs.

4 Object catalogs

We used the catalogs of extragalactic objects resulting from measurements at different wavelengths as listed in Table 1. In several catalogs, the objects near the Galactic plane were excluded to avoid observational incompleteness by the authors of each catalog. We have also exclude the observed SD events in the corresponding regions.

The 3CRR catalog contains radio galaxies detected at 178 MHz with fluxes greater than 10 Jy [20]. The 2MRS [21] catalog is derived from the 2MASS observation with the detection range of $1-2$ μm with $K_s \leq 11.75$ magnitude. The SB-58M catalog consists of the objects which were detected with the significance greater than 4.8σ in the energy range of $14-195$ keV in the first 58 months of observation by Swift BAT. We chose the extragalactic objects in this catalog for this work. The catalog of SB-AGN contains the AGN with more than 5σ detection in the energy range of $15-55$ keV in the first 60 month of observation by Swift BAT. The 2LAC [24] consists of AGNs detected with the significance more than 4σ in the energy range of 100 MeV$-$100 GeV in the first 24 months of observation by Fermi-LAT. We also examine the VCV catalog which is a compilation of several AGN surveys.

5 Results

The results of the parameter scan are listed in Table 2. 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 parameter set of $(E_{\rm min}, \psi, z_{\rm max})_{\rm best} = (62.20\ {\rm EeV}, 10°, 0.020)$. 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.

Next, we consider a penalty for the parameter scanning. We evaluated the probability $P_{\rm pps}$ of finding a correlation by chance with $P_{\rm min}^{\rm sim}$ smaller than that obtained from the data (for more detail see e.g., [28]). We generated 104 mock event 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 in the same way as in the observed data set, and $P_{\rm min}^{\rm sim}$ was calculated. 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 2. The smallest value of $P_{\rm pps}$ among the catalogs is 0.01 from the the SB-AGN catalog, not yet including 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. So, we have repeated the simulation with 104 mock sets as described above, but with the scanning performed in all 6 catalogs. Calculating the fraction of mock sets that show equal or better correlation than the data we found 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.

6 Summary

We examined the correlations between the observed UHECR arrival directions and the extragalactic objects from the different wavelength survey catalogs. We used the TA-SD events with energies greater than 40 EeV obtained in the first 40 months of observation. We searched for maximum correlations by scanning over three parameters $E_{\rm min}$, ψ, and $z_{\rm max}$ in 6 different catalogs. The smallest chance probability among these 6 catalogs was found with the Swift BAT (60-month) AGN catalog, $P_{\rm min}^{\rm obs} = 1.3 \times 10^{-5}$. 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.

Acknowledgment: The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) "Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays", and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, PHY-0848320, PHY-1069280, and PHY-1069286 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions as well as the University of Utah Center for High Performance Computing (CHPC).

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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 2: Summary of correlations with the best parameter set (minimum threshold, Window size, maximum redshift) for each catalog. A: number of objects with the redshift $\leq z_{\rm th}$, N: number of observed cosmic ray events with the energy $E \geq E_{\rm th}$, k: number of correlated events 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 includes penalties from parameter scanning.