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Testing a Reported Correlation between Arrival Directions of Ultra-high-energy Cosmic Rays and a Flux Pattern from nearby Starburst Galaxies using Telescope Array Data

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Abstract

The Pierre Auger Collaboration (Auger) recently reported a correlation between the arrival directions of cosmic rays with energies above 39 EeV and the flux pattern of 23 nearby starburst galaxies (SBGs). In this Letter, we tested the same hypothesis using cosmic rays detected by the Telescope Array experiment (TA) in the 9 yr period from 2008 May to 2017 May. Unlike the Auger analysis, we did not optimize the parameter values but kept them fixed to the best-fit values found by Auger, namely 9.7% for the anisotropic fraction of cosmic rays assumed to originate from the SBGs in the list and 12°.9 for the angular scale of the correlations. The energy threshold that we

[35] Deceased.

adopted is 43 EeV, corresponding to 39 EeV in Auger when taking into account the energy-scale difference between two experiments. We find that the TA data is compatible with isotropy to within 1.1σ and with the Auger result to within 1.4σ, meaning that it is not capable to discriminate between these two hypotheses.

Key words: astroparticle physics – cosmic rays – galaxies: starburst – methods: data analysis

1. Introduction

The origins of ultra-high-energy cosmic rays (UHECRs) are still unknown. Anisotropies in the angular distribution of their arrival directions are rather small, requiring the detection of a large number of events to observe them. Furthermore, deflections of UHECRs by Galactic and intergalactic magnetic fields complicate the interpretation of anisotropies in terms of possible sources; this effect is reduced for the highest-energy cosmic rays, but the available statistics are significantly limited due to the steeply falling spectrum of UHECRs.

The two largest UHECR observatories in operation are the Telescope Array (TA; Abu-Zayyad et al. 2013a), located in Utah, USA, with approximately 700 km^2 effective area, and the Pierre Auger Observatory (Auger; Aab et al. 2015), located in Argentina with 3000 km^2 effective area. Their exposures peak in the Northern and Southern hemispheres, respectively.

Auger recently reported (Aab et al. 2018) a correlation between UHECR events with reconstructed energies above 39 EeV and a flux pattern of nearby starburst galaxies (SBGs). A model where 90.3% of the flux is isotropic and 9.7% originates from SBGs (with UHECR luminosities assumed to be proportional to their radio luminosities) and undergoes Gaussian random deflections with standard deviation 12°.9 in each transverse dimension is favored over the purely isotropic model with a post-trial significance of 4.0σ, and over a model based on the overall galaxy distribution beyond 1 Mpc with a 3.0σ significance. In the Auger analysis it was found that different selections of candidate sources yield very similar results, as in any case over 90% of the anisotropic part of the flux weighed by the Auger directional exposure originates from four bright objects—NGC 4945, NGC 253, M83, and NGC 1068.

In this Letter, we follow up on this finding by testing UHECRs detected by TA in the Northern hemisphere against the same flux model and the best-fit values reported by Auger, and discuss possible interpretations of our result.

2. Analysis

2.1. Cosmic-Ray Data Set

The TA is located at 39°.3N, 112°.9W, in Millard County, Utah, USA, about 200 km southwest of Salt Lake City, about 1400 m above sea level (Abu-Zayyad et al. 2013a). The TA surface detector (SD) array consists of 507 plastic scintillation detectors on a square grid with 1.2 km spacing, covering an area of 700 km^2, and is surrounded by three fluorescence detector (FD) stations (Tokuno et al. 2012) with telescopes overlooking the SD array. It has been collecting data since 2008 May. The SD has ≈100% duty cycle, against ≈10% for the FD, so with a similar collection area the SD has about 10 times the statistics. The events detected in coincidence by both detectors are used to calibrate energy scale of the SD: SD reconstructed energies (determined by comparison to Monte Carlo simulations) are rescaled by a factor of 1/1.27 to match the FD energy scale (determined calorimetrically; Abu-Zayyad et al. 2013b; Tsunesada et al. 2017). The systematic uncertainty on the TA energy scale is 21% (Abbasi et al. 2016) and its energy and angular resolutions are 15%–20% and 1°.0–1°.5, respectively, depending on the event geometry and energy (Abbasi et al. 2014).

In this Letter we use data collected by the TA SD array in a 9 yr period from 2008 May to 2017 May with reconstructed energies above 43 EeV, zenith angles less than 55°, and declinations $\delta > -10°$ using the same quality cuts as in Abbasi et al. (2014). This data set comprises 284 events. We neglect the finite angular and energy resolution of TA events, and consider the detector fully efficient, i.e. with a flat response for all showers with energies and zenith angles in the considered range, so that its directional exposure ω_{TA} equals the geometrical one for $\delta > -10°$, which varies with declination but not with right ascension (Sommers 2001):

$$\omega_{\mathrm{TA}}(\delta) \propto \cos\phi_{\mathrm{TA}} \cos\delta \sin\alpha_{\mathrm{m}} + \alpha_{\mathrm{m}} \sin\phi_{\mathrm{TA}} \sin\delta,$$
$$\alpha_{\mathrm{m}} = \begin{cases} \pi, & \xi < -1; \\ \arccos\xi, & -1 \leqslant \xi \leqslant 1; \\ 0, & \xi > 1; \end{cases}$$
$$\xi = \frac{\cos\theta_{\mathrm{m}} - \sin\phi_{\mathrm{TA}} \sin\delta}{\cos\phi_{\mathrm{TA}} \cos\delta}, \qquad (1)$$

where $\phi_{\mathrm{TA}} = +39°.3$ is the detector latitude and $\theta_{\mathrm{m}} = 55°$ is the maximum zenith angle accepted.

The energy threshold of $E_{\mathrm{min}} = 43$ EeV used in this analysis corresponds to the Auger energy threshold of 39 EeV, at which the most significant correlation with SBG was found. Here we took into account the 10.4% difference between the energy scales of the two experiments as estimated by a comparison of energy spectra around 5 EeV (Verzi et al. 2017; Abu-Zayyad et al. 2018).

2.2. Source Catalog

Following the Auger analysis (Aab et al. 2018), we select the candidate sources from a sample of 63 SBGs outside the Local Group compiled by the *Fermi*-Large Area Telescope (LAT) Collaboration (Ackermann et al. 2012) for the gamma-ray emission search.[36] Imposing the cut of flux greater than 0.3 Jy at 1.4 GHz leaves 23 objects in the catalog of candidate sources. Their UHECR fluxes were assumed to be proportional to their radio fluxes at 1.4 GHz. These objects are listed in Table 1.

In the Auger analysis, the effect of energy losses by UHECRs during their propagation was found to be negligible in the SBG model, as most of the anisotropic flux originates from sources within a few Mpc; in this Letter, we neglected the losses for simplicity.

2.3. Test Statistic and Flux Model

Let $\hat{\boldsymbol{n}}$ be the unit vector representing a direction in the sky, pointing away from the observer. Given two flux models

[36] Only four of those objects were actually successfully detected in gamma-rays in that work: NGC 253, M82, NGC 4945, and NGC 1068.

Table 1
Selected Source Candidates from the SBG Catalog used in this Analysis (the same as in Aab et al. 2018)

Name	Gal. (l, b)		Distance	Flux ϕ	$\phi\omega_{\rm TA}$
NGC 253	97°.4	−88°.0	2.7 Mpc	13.6%	1.6%
M82	141°.4	40°.6	3.6 Mpc	18.6%	35.7%
NGC 4945	305°.3	13°.3	4.0 Mpc	16.0%	0.0%
M83	314°.6	32°.0	4.0 Mpc	6.3%	0.4%
IC 342	138°.2	10°.6	4.0 Mpc	5.5%	10.5%
NGC 6946	95°.7	11°.7	5.9 Mpc	3.4%	6.2%
NGC 2903	208°.7	44°.5	6.6 Mpc	1.1%	1.4%
NGC 5055	106°.0	74°.3	7.8 Mpc	0.9%	1.5%
NGC 3628	240°.9	64°.8	8.1 Mpc	1.3%	1.5%
NGC 3627	242°.0	64°.4	8.1 Mpc	1.1%	1.2%
NGC 4631	142°.8	84°.2	8.7 Mpc	2.9%	4.4%
M51	104°.9	68°.6	10.3 Mpc	3.6%	6.2%
NGC 891	140°.4	−17°.4	11.0 Mpc	1.7%	2.8%
NGC 3556	148°.3	56°.3	11.4 Mpc	0.7%	1.3%
NGC 660	141°.6	−47°.4	15.0 Mpc	0.9%	1.0%
NGC 2146	135°.7	24°.9	16.3 Mpc	2.6%	5.2%
NGC 3079	157°.8	48°.4	17.4 Mpc	2.1%	3.8%
NGC 1068	172°.1	−51°.9	17.9 Mpc	12.1%	9.1%
NGC 1365	238°.0	−54°.6	22.3 Mpc	1.3%	0.0%
Arp 299	141°.9	55°.4	46.0 Mpc	1.6%	2.9%
Arp 220	36°.6	53°.0	80.0 Mpc	0.8%	1.1%
NGC 6240	20°.7	27°.3	105.0 Mpc	1.0%	0.8%
Mkn 231	121°.6	60°.2	183.0 Mpc	0.8%	1.4%

Note. The last column shows the relative source contribution weighted with the TA directional exposure $\omega_{\rm TA}$.

$\Phi_1(\hat{\boldsymbol{n}})$, $\Phi_2(\hat{\boldsymbol{n}})$ describing a null hypothesis and an alternative hypothesis, respectively, and the directional exposure $\omega(\hat{\boldsymbol{n}})$ of an experiment, the test statistic (hereinafter TS) is defined as twice the log-likelihood ratio

$$\mathrm{TS} = 2\ln\left(L(\Phi_2)/L(\Phi_1)\right),$$
$$\text{where } L(\Phi_j) = \prod_i \frac{\Phi_j(\hat{\boldsymbol{n}}_i)\omega(\hat{\boldsymbol{n}}_i)}{\int_{4\pi}\Phi_j(\hat{\boldsymbol{n}})\omega(\hat{\boldsymbol{n}})\,\mathrm{d}\Omega}, \quad (2)$$

and $\hat{\boldsymbol{n}}_i$ being the reconstructed arrival direction of the i-th observed event. A positive (negative) TS indicates that the data set is more (less) likely if the real flux is described by $\Phi_2(\hat{\boldsymbol{n}})$ than by $\Phi_1(\hat{\boldsymbol{n}})$.

In this analysis, the null hypothesis is an isotropic flux, $\Phi_1(\hat{\boldsymbol{n}}) = \Phi_{\rm iso} = 1/4\pi$, whereas the alternative hypothesis is $\Phi_2(\hat{\boldsymbol{n}}) =$

$$\Phi_{\rm mod}(\hat{\boldsymbol{n}}) = f_{\rm SBG}\,\Phi_{\rm SBG}(\hat{\boldsymbol{n}}) + (1 - f_{\rm SBG})\Phi_{\rm iso}, \quad (3)$$

where $f_{\rm SBG} = 9.7\%$ is the fraction of the flux assumed to originate from the SBGs in the catalog (the rest being assumed to be isotropic), and

$$\Phi_{\rm SBG}(\hat{\boldsymbol{n}}) = \frac{\sum_k \phi_k \exp(\hat{\boldsymbol{n}}_k \cdot \hat{\boldsymbol{n}}/\theta^2)}{\int_{4\pi}\sum_k \phi_k \exp(\hat{\boldsymbol{n}}_k \cdot \hat{\boldsymbol{n}}/\theta^2)\,\mathrm{d}\Omega} \quad (4)$$

is a weighed sum of von Mises–Fisher distributions (the spherical analog of the Gaussian distribution), where ϕ_k and $\hat{\boldsymbol{n}}_k$ are the flux and position of the k-th source from Table 1 and $\theta = 12°.9$ is the rms deviation in each transverse dimension, the total rms deviation being $\sqrt{2}\,\theta$. The exposure is assumed to be geometrical, $\omega(\hat{\boldsymbol{n}}) = \omega_{\rm TA}(\hat{\boldsymbol{n}})$ from Equation (1). In this Letter we do not optimize the parameter values but keep them fixed to the Auger best-fit values, in order not to include any freedom in the model which would require a statistical penalty. The resulting model flux is shown in Figure 1, along with the events in the TA data set.

3. Results

Substituting the coordinates of the TA events $\{\hat{\boldsymbol{n}}_i\}$ into Equation (2), the test statistic that we obtained was $\mathrm{TS} = -1.00$. In order to assess the significance of this result, we computed TS for 10^6 Monte Carlo (MC) data sets generated assuming an isotropic flux, and found $\mathrm{TS} \geqslant -1.00$ in $p = 14.3\%$ of the 10^6 cases, corresponding to a 1.1σ significance.[37]

We also computed test statistics for 10^6 MC sets generated under an assumption of the Auger best-fit SBG flux model to know the range of TS values that could be expected in that case. The results are shown in Figure 2. We found that 92.5% of realizations in the latter case have a higher TS value than the TA data (corresponding to a -1.4σ significance). We also verified that, as should be by design, the ratio between the two TS distributions is $\exp(\mathrm{TS}/2)$. A negative TS means that the angular distribution in a data set resembles isotropy more than the SBG model, and a positive TS means the reverse, so most isotropic realizations have $\mathrm{TS} < 0$ and most SBG-like realizations have $\mathrm{TS} > 0$. $\mathrm{TS} \approx 0$ would mean that the angular distribution in a data set is about equally different from the two models considered.

4. Discussion

A limitation in this analysis is the exclusion of Local Group objects (Small Magellanic Cloud (SMC), Large Magellanic Cloud (LMC), M33, and M31), which were listed in Ackermann et al. (2012) but in a separate table. These objects are not particularly intrinsically luminous (several times less than the dimmest objects in Table 1), but due to their proximity ($D = 0.06$, 0.05, 0.85, and 0.78 Mpc, respectively) they appear very bright. If the assumed proportionality between the UHECR luminosity, the star formation rate and the radio luminosity also applied to them, then the LMC and SMC would outshine all other objects combined in the Auger sky, and M33 and M31 would be the second- and third-brightest objects in the TA sky; but no excess of events is apparent in the vicinity of either pair of objects in our data or in Aab et al. (2018). A discussion about possible theoretical astrophysical motivations for not including these objects in the sample is outside the scope of this Letter.

Aab et al. (2018) also tested their data for correlations with gamma-ray loud active galactic nuclei from the second catalog of hard *Fermi*-LAT sources (Ackermann et al. 2016). The best fit ($E_{\rm min} = 60$ EeV, $f_{\gamma\rm AGN} = 6.7\%$, $\theta = 6°.9$) is favored over isotropy at the 2.7σ level. Unlike with SBGs, UHECR energy losses in propagation are not negligible in this case because the unattenuated flux is not dominated by nearby objects. Testing TA data for correlations with this catalog would not be very useful, because the attenuated flux at Earth is dominated by Cen A, way outside of the TA field of view (at $\delta = -43°$), leaving the flux in the northern hemisphere very nearly isotropic, and therefore requiring a very large number of

[37] Note that unlike in the Auger analysis, Wilks' theorem is not applicable here because we did not scan a parameter space of which the null hypothesis is a subspace.

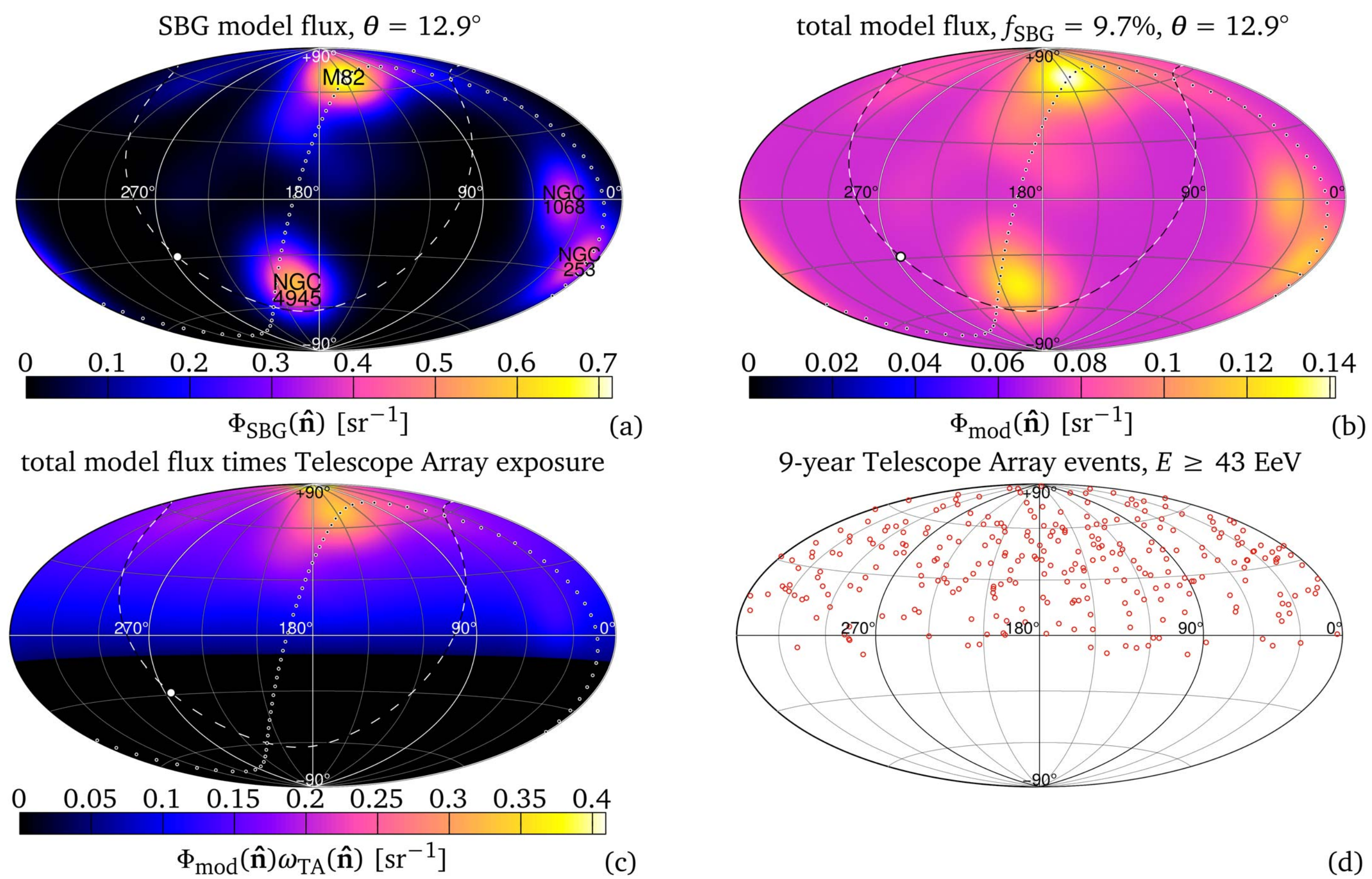

Figure 1. Maps of: (a) the anisotropic part of the model flux (Equation (4)); (b) the total model flux (Equation (3)); (c) the total model flux multiplied by the TA exposure; and (d) the TA events above 43 EeV. The dashed and dotted lines represent the Galactic and supergalactic planes, respectively, and the white disk shows the Galactic center.

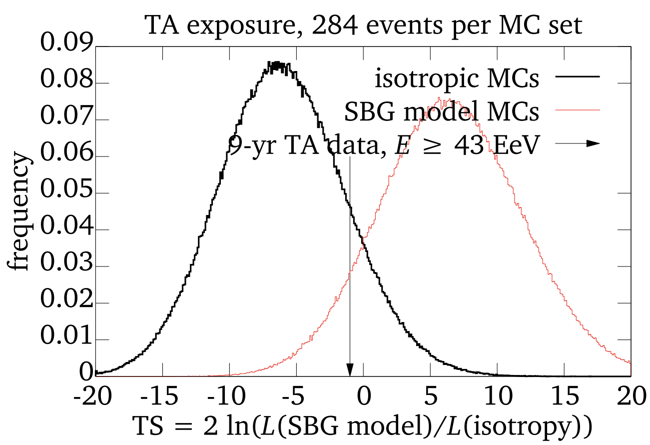

Figure 2. Distribution of test statistics in MC sets generated according to the two flux hypotheses that we considered.

events for an experiment in the northern hemisphere to detect the correlation; also, the Auger best-fit energy threshold found with this catalog ($E_{\min} = 60$ EeV) was higher than with the SBGs, further reducing the available statistics.

5. Conclusions

This Letter presents the result of a search for a correlation between arrival directions of UHECRs observed by TA and the flux pattern of SBGs. The SBG sample, anisotropic fraction, and angular scale were fixed to be the best-fit values as in the Auger study. The energy threshold of 43 EeV was determined by taking into account of the energy-scale difference between two experiments (Abu-Zayyad et al. 2018), corresponding to 39 EeV, at which the most significant correlation was reported in Auger. The result of this test was inconclusive, being compatible both with isotropy to within 1.1σ and with the Auger result to within 1.4σ. This means that the current TA data is not capable of discriminating between these two hypotheses. The ongoing expansion of TA (Kido 2018) will increase its effective area by a factor of 4, allowing us to reduce the statistical uncertainties and possibly to discriminate between different hypothesis about the UHECR origin.

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