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UHECR results of combined analyses of TA and Auger experiments

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Abstract. The origin of ultra-high-energy cosmic rays (UHECRs) is still unknown. Their sources are believed to be within the local universe (a few hundred megaparsecs), but deflections by intergalactic and Galactic magnetic fields prevent us from straightforwardly associating UHECRs to their sources based on their arrival directions, making their angular distribution mostly isotropic. At higher energies, the number of potential source candidates and the magnetic deflections are both expected to be smaller, but so is the available amount of statistics. Hence, it is interesting to perform searches for anisotropies using several different energy thresholds. With a threshold of 8 EeV a dipole modulation has been discovered, and with higher thresholds evidence is mounting for correlations with certain nearby galaxies. Neither of the two main UHECR detectors, the Pierre Auger Observatory and the Telescope Array project, has full-sky coverage. Full-sky searches require combining the datasets of both, and a working group with members of both collaborations has been tasked with this. We present an overview of the challenges encountered in such analyses, recent results from the working group, possible ways of interpreting them, and an outlook for the near future.

1 Introduction

1.1 Ultra-high-energy cosmic rays (UHECRs)

Particles with energies $E \geq 1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV} \approx 0.16\,\mathrm{J}$ are known as ultra-high-energy cosmic rays (UHECRs). UHECRs can be detected by huge arrays of particle detectors on the ground, and they are electrically charged (atomic nuclei, mostly protons); as a result, they are deflected by intergalactic and Galactic magnetic fields by $O(30Z(E/10\,\mathrm{EeV})^{-1})^\circ$, where Z is their electric charge, and do not directly point back to their sources. Their arrival directions are nearly isotropically distributed over the full sky: it took 32,000 events for the first anisotropy to be detected with $\geq 5\sigma$ significance (a 6.5% dipole[1] at $E \geq 8\,\mathrm{EeV}$ [2]). It is still not known where or how UHECRs achieve such energies. At the highest energies, their propagation is limited to distances $O(10^2\,\mathrm{Mpc})$ by interactions with cosmic background photons.

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[1] As of last update [1] using 44,000 events, the estimate of the dipole magnitude has been revised to 7.3% and its significance has increased to 6.6σ.

1.2 The main UHECR detector arrays: Auger and TA

The largest cosmic-ray detector arrays in the world are the Pierre Auger Observatory ("Auger") in Argentina and the Telescope Array (TA) in Utah, USA. Neither TA alone nor Auger alone covers the full sky: TA can only observe the full northern celestial hemisphere and the parts of the southern one closest to the equator (declinations $\delta > -15.7°$), and Auger vice versa (declinations $\delta < +44.8°$). Hence, we can get full-sky coverage by combining the two, and furthermore their fields of view overlap in a band surrounding the celestial equator.

Several joint working groups of members from both the Auger and the TA collaboration have been established since the early 2010s to perform full-sky studies of the energy spectrum, mass composition and arrival directions of UHECRs, as well as direct calibrations of Auger SD stations at the TA site. Certain working groups also include members from other collaborations, such as that on hadronic interactions and shower physics (with EAS-MSU, IceCube, KASCADE-Grande, NEVOD-DECOR, SUGAR and Yakutsk members) and that on neutrino–UHECR angular correlations (with ANTARES and IceCube members). The results from the joint working groups, mainly presented at the International Symposium on Ultra-High-Energy Cosmic Rays (UHECR) and the International Cosmic Ray Conference (ICRC), are listed at http://tiny.cc/Auger-TA. The data used for the latest Auger–TA joint analyses on arrival directions, presented at ICRC 2021 [3, 4], comprise events detected by Auger in the 17 yr period from 1 January 2004 to 31 December 2020 (with an effective exposure of 123,200 km^2 yr sr and 39,157 events with $E \geq 8.57\,\mathrm{EeV}$, of which 2,625 with $E \geq 32$ EeV) and by TA in the 11 yr period from 11 May 2008 to 10 May 2019 (with an effective exposure of 13,700 km^2 yr sr and 4,801 events with $E \geq 10\,\mathrm{EeV}$, of which 315 with $E \geq 40.8\,\mathrm{EeV}$).

1.3 The issue of the cross-calibration of the energy scales

UHECR energy measurements are affected by sizable systematic uncertainties (±14% for Auger, ±21% for TA). If not corrected, a mismatch between energy scales can yield a spurious dipole. (For example, if events with $E_{\mathrm{true}} = 10\,\mathrm{EeV}$ are reconstructed as $E_{\mathrm{rec}} = 9\,\mathrm{EeV}$ by Auger and as $E_{\mathrm{rec}} = 11\,\mathrm{EeV}$ by TA, and we collect all events with $E_{\mathrm{rec}} \geq 10\,\mathrm{EeV}$, then events with $E_{\mathrm{true}} = 10\,\mathrm{EeV}$ are included if detected by TA but not if detected by Auger, which would appear as if the UHECR flux from the north were larger than from the south.) Hence, possible mismatches in the energy scales should be corrected to the best of our abilities. Measurements in the common declination band can be used for this purpose.

At ICRC 2021 [3], we simultaneously fitted a twice-broken power-law model for the energy spectrum and a power-law model for the $E_{\mathrm{Auger}} \leftrightarrow E_{\mathrm{TA}}$ conversion to the data in a common declination band, obtaining

$$\frac{E_{\mathrm{Auger}}}{10\,\mathrm{EeV}} = 0.857\left(\frac{E_{\mathrm{TA}}}{10\,\mathrm{EeV}}\right)^{0.937}, \qquad \frac{E_{\mathrm{TA}}}{10\,\mathrm{EeV}} = 1.179\left(\frac{E_{\mathrm{Auger}}}{10\,\mathrm{EeV}}\right)^{1.067}.$$

Note that in this fit we used datasets optimized for anisotropy studies at $E_{\mathrm{TA}} \geq 10\,\mathrm{EeV}$, hence the result must not be extrapolated to lower energies or used outside of the scope of this analysis.

2 Latest results (shown at ICRC 2021)

2.1 Large-scale anisotropies: dipoles and quadrupoles

The flux Φ of UHECRs as a function of the arrival direction $\hat{\mathbf{n}}$ can be expanded into spherical harmonics as $\Phi(\hat{\mathbf{n}}) = \sum_{\ell=0}^{+\infty}\sum_{m=-\ell}^{+\ell} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}) = \Phi_{\mathrm{avg}} \times \left(1 + \mathbf{d}\cdot\hat{\mathbf{n}} + \frac{1}{2}\hat{\mathbf{n}}\cdot \mathsf{Q}\hat{\mathbf{n}} + \cdots\right)$, where

Table 1. Our measurements of the dipole and quadrupole moments [3]. The first uncertainty is statistical, the second is due to the uncertainty in the cross-calibration of energy scales. Values in *italics* (***bold***) are locally significant at ≥ 2σ (≥ 4σ).

energies (Auger) energies (TA)	[8.57 EeV, 16 EeV) [10 EeV, 19.47 EeV)	[16 EeV, 32 EeV) [19.47 EeV, 40.8 EeV)	[32 EeV, +∞) [40.8 EeV, +∞)
d_x [%]	−0.7 ± 1.1 ± 0.0	+1.6 ± 2.0 ± 0.0	−5.3 ± 3.9 ± 0.1
d_y [%]	***+4.8 ± 1.1 ± 0.0***	*+3.9 ± 1.9 ± 0.1*	*+9.7 ± 3.7 ± 0.0*
d_z [%]	−3.3 ± 1.4 ± 1.3	−6.0 ± 2.4 ± 1.3	+3.4 ± 4.7 ± 3.6
$Q_{xx} - Q_{yy}$ [%]	−5.1 ± 4.8 ± 0.0	+13.6 ± 8.3 ± 0.0	*+43 ± 16 ± 0*
Q_{xz} [%]	−3.9 ± 2.9 ± 0.1	+5.4 ± 5.1 ± 0.0	+5 ± 11 ± 0
Q_{yz} [%]	−4.9 ± 2.9 ± 0.0	−9.6 ± 5.0 ± 0.1	+11.9 ± 9.8 ± 0.2
Q_{zz} [%]	+0.5 ± 3.3 ± 1.7	+5.2 ± 5.8 ± 1.7	+20 ± 11 ± 5
Q_{xy} [%]	+2.2 ± 2.4 ± 0.0	+0.2 ± 4.2 ± 0.1	+4.5 ± 8.1 ± 0.1

coefficients with small ℓ correspond to large-scale ($\sim 180°/\ell$) anisotropies and vice versa. The dipole moment **d** is given by $\sqrt{3}(a_{11}\hat{\mathbf{x}} + a_{1-1}\hat{\mathbf{y}} + a_{10}\hat{\mathbf{z}})/a_{00}$, and likewise the components of the quadrupole moment Q are combinations of a_{2m}/a_{00} ($m = -2, -1, 0, +1, +2$).

The dipole amplitude $|\mathbf{d}|$ and the quadrupole amplitude $|\mathsf{Q}|$ are relatively insensitive to magnetic fields, providing some information about sources: coherent deflections mainly affect the directions of **d**, Q rather than their amplitudes, and turbulent deflections only attenuate the 2^ℓ-upole by a factor $O\left(\exp(-\ell^2\Delta\theta^2_{\text{turb}}/2)\right)$, so that most of the $|\mathbf{d}|$ and a sizable fraction of the $|\mathsf{Q}|$ should survive (see also ref. [5]).

With full-sky coverage it is possible to measure the first two multipoles a_{1m} and , a_{2m} in a way that is unbiased regardless of any assumption made about higher multipoles [3]. The results are listed in table 1.

We do not find any deviations from isotropy other than a weakly energy-dependent dipole towards a direction far away from the Galactic Center and a hint of a quadrupole at the highest energies roughly along the Supergalactic Plane. The reconstructed strength of large-scale anisotropies is at the low edge of the range of model expectations such as those of refs. [6, 7], suggesting a medium to heavy mass composition.

2.2 Medium-scale anisotropies: correlations with nearby galaxies

Unlike large-scale anisotropies, in order to search for medium-scale anisotropies we need to focus on the highest energies, where magnetic deflections are expected to be smaller, though this severely reduces the amount of statistics available, making "blind" searches very unlikely to yield strongly significant results. Hence, we performed targeted searches based on two different catalogs, one comprising all types of galaxies at distances between 1 and 250 Mpc, and one comprising starburst galaxies at distances between 1 and 130 Mpc, described in ref. [4] and refs. therein. The test statistic (TS) we used is twice the log-likelihood ratio between a model consisting of an isotropic background plus a weighted sum of Fisher distributions and the isotropic null hypothesis, scanned over the energy threshold $E_{\min}$, the angular scale ψ, and the signal fraction f.

The most significant correlation we found is TS = 27.2 with the starburst galaxy catalog, using $E_{\min} = 38\,\text{EeV}$ on the Auger scale (49 EeV on the TA scale), $\psi = 15.5°^{+5.3°}_{-3.2°}$, and $f = 11.8\%^{+5.0\%}_{-3.1\%}$; the observed flux and the model prediction are compared in figure 1. The post-trial significance of this is 4.2σ. We also found a correlation TS = 16.2 with the general galaxy catalog, using $E_{\min} = 41\,\text{EeV}$ on the Auger scale (53 EeV on the TA scale), $\psi = 24°^{+13°}_{-8°}$, and $f = 38\%^{+28\%}_{-14\%}$, though the post-trial significance of this is only 2.9σ.

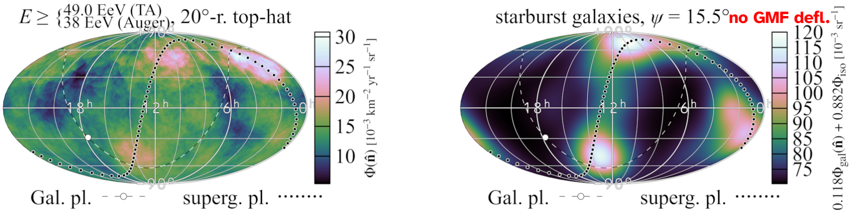

Figure 1. The observed UHECR flux above 38 EeV, compared to the starburst galaxy model predictions

3 Outlook

3.1 Estimating propagation effects on correlation searches via simulations

In order to reduce statistical penalties, the TS was based on a simple model, not taking into account the energy losses of UHECRs (which depend on their mass composition), coherent magnetic deflections, and the possibility of several anisotropic classes of sources at once. In order to estimate their effects, we plan to generate simulated datasets based on a variety of scenarios, subject each of them to the same analyses as the real data at ICRC 2021, and look at which simulations result in similar ψ, f, TS as the real data. The result of such studies will be presented at future conferences.

3.2 Extended datasets

An update of these analyses using three more years of TA data was presented at UHECR 2022 [8], and a further update will be presented at ICRC 2023 using as much Auger and TA data as will be available by then, which we can expect to reduce statistical uncertainties by around 10% compared to those shown here. Continued work by the spectrum working group might reduce uncertainties in the energy cross-calibration even more than this.

3.3 Next-generation experiments and mass-dependent anisotropies

TA is undergoing an upgrade (TA×4) which will increase its area by a factor of 4, helping reduce statistical uncertainties in the northern hemisphere. Auger is undergoing an upgrade (AugerPrime) which will add new scintillation and radio detectors to the existing water-Cherenkov and fluorescence detectors, reducing statistical and systematic uncertainties on UHECR masses. Better UHECR mass estimates will help us study mass-dependent anisotropies, potentially allowing us to disentangle the effects of magnetic deflections from the distribution of UHECR sources. In the farther future, new experiments such as GRAND, POEMMA and GCOS are hopefully going to gather even more data.

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