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Medium-scale anisotropies in the arrival directions of UHECRs observed by the Pierre Auger Observatory

C. Galelli([1])([2]) on behalf the Pierre Auger Collaboration([*])

([1]) *INFN, Sezione di Milano - Milano, Italy*
([2]) *Dipartimento di Fisica, Università di Milano - Milano, Italy*

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Summary. — The most prominent obstacle to identifying the sources of Ultra-High-Energy Cosmic Rays (UHECRs) is their incredibly low flux. For this reason, the Pierre Auger Observatory covers an area of $\sim$3000 km^2 and, in its 17 years of operation, has collected over 2600 UHECR events with energies above 32 EeV. In this contribution, I present the search of this dataset for anisotropies on medium scales of a few tenths of degrees in the arrival directions of UHECRs. Evidence for an overdensity in the Centaurus region of the sky is obtained at the 4σ significance level; this evidence is corroborated by a catalog-based likelihood ratio analysis comparing the dataset against the distribution of the closest radiogalaxies and starburst galaxies.

1. – Introduction

The cosmic ray beam includes the most energetic particles in the known universe, with energies reaching and surpassing 100 EeV, or 10^{20} eV. Understanding their origins can then shed light on some of the most powerful engines in existence. Unfortunately, the search for cosmic ray sources is complicated by the fact that they are predominantly charged particles, and as such, they are deflected by the magnetic fields which are present in galaxies and in the extragalactic medium; moreover, these fields are not yet understood to a degree sufficient to produce reliable models. However, at high enough energies, typically above the tens of EeV, deflection should be small enough to retain information on the original arrival direction, provided that the cosmic ray has a small enough charge. Data from the Pierre Auger Observatory shows a dipolar feature in the arrival directions

([*]) Observatorio Pierre Auger - Av. San Martín Norte 304, 5613 Malargüe, Argentina.
Full author list: `https://www.auger.org/archive/authors_2021_09.html`.
E-mail: `spokespersons@auger.org`

of UHECRs with energies above 8 EeV. Since the direction of this dipole points away from the Galactic Center and is consistent with the local distribution of galaxies at the 2σ significance level, this result strongly disfavors a Galactic origin for high-energy events [1].

Fortunately, however, one does not need to look for the sources in the whole universe, but can limit the search to a relatively small volume thanks to the interaction of the primary cosmic rays with the cosmic microwave background photons (the so-called GZK effect) [2, 3]; in particular, heavy nuclei can photodissociate, and protons can produce pions via a delta resonance. The portion of the local universe that can be observed via UHECRs is then limited; the size of the bubble depends on the energy and mass of the specific particle. At 100 EeV, for example, the horizon is of the order of 100–300 Mpc for iron nuclei and protons, and much smaller for intermediate particles.

2. – Dataset

The Pierre Auger Observatory [4] is the largest cosmic ray detection facility ever built. It is composed of an array of 1660 Cherenkov surface detector (SD) stations distributed in a grid spanning over $\sim$3000 km^2 of *pampa* near the town of Malargüe, Argentina, and a set of 27 fluorescence detector (FD) telescopes that overlook the grid. Both components detect UHECRs indirectly by the showers of secondary particles (EAS) that are produced by the interaction of the primary cosmic rays with molecules in the atmosphere.

The dataset used in this work contains 2625 events collected by the SD with energies above 32 EeV, between 01/01/2004 and 31/12/2020. This is the period of the *Auger Phase One*, before the upgrade called Auger Prime that is being installed in the field at the time of writing. The SD has the advantage of a duty cycle close to 100%, as it samples the EAS at ground level, allowing the creation of the largest dataset possible. The detector is sensitive to EASs with zenith angles between 0 and 80 degrees. Events with θ under 60° are called *vertical* and were used in this analysis if the SD station with the highest signal was surrounded by at least four other active stations; those with θ between 60° and 80° are called *inclined* and were used if the reconstructed center of the EAS fell between at least five active stations. This selection resulted in a dataset of 2032 vertical and 593 inclined events.

3. – Analysis

This contribution updates the results published previously [5] with the final dataset of Auger Phase One. Three types of analyses are presented: a blind overdensity search, a catalog-based likelihood-ratio test, and a targeted search around the Centaurus region of the sky.

3·1. *Blind search for overdensities.* – The search for overdensities was performed in the whole portion of the sky visible by the Observatory; to do so, the sky is divided into pixels of area comparable to the resolution of the Observatory using HEALPix. The observed number of events within an angular window Ψ is compared to the number of events expected from an isotropic background. Search radiuses between 1 and 30 degrees and energy thresholds between 32 EeV and 80 EeV are scanned. To take into account these trials, the *post-trial* p-value was calculated as the fraction of isotropic simulations of the same size as the original dataset that have a lower p-value than that. The local Li-Ma significance was also computed. The most significant excess is found at energy

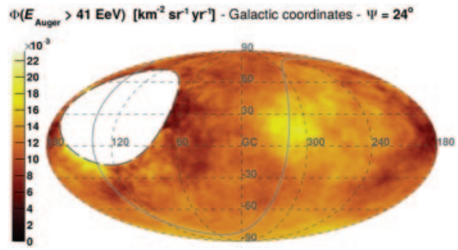

Fig. 1. – Flux map of UHECRs with energies above 41 EeV in Galactic Coordinates with a top-hat of radius 24°.

threshold of 41 EeV, and a radius Ψ of 24° centered on Galactic coordinates $(l, b) = (1.3°, 322.4°)$, in the Centaurus region (fig. 1). The local p-value in this position is 1.3×10^{-7}, resulting in a post-trial p-value of 2%.

3˙2. *Catalog-based searches.* – A more refined analysis was conducted by cross-correlating the observed UHECR flux with four catalogs of nearby galaxies grouped by emission bands: the 2MASS [6] in infrared tracing all galaxies, Swift-BAT 105 months [7] in hard X-ray for all Active Galactic Nuclei (AGN), Fermi-3FHL [8] in γ-rays for jetted AGNs and Lunardini-19 [9] in radio for starburst galaxies. The relevant Test Statistic (TS) is computed for each of the four catalogs and maximized as a function of the two free parameters of the model: the search radius θ, the angular dimension of the window for the counting of events, and the signal fraction α, the portion of events that are considered as originating from the sources in question. The results are then penalized for the scan in threshold energy. The best fit was obtained with the Starburst catalog at threshold energy 38 EeV, $\theta = 15.3°$ and $\alpha = 9.2$, with a TS of 24.9 and a post-trial p-value of 3.1×10^{-5}. The significance is driven mostly by the presence of the previously mentioned hotspot of events in the Centaurus region, where two prominent starburst galaxies, M83 and NGC4945, are present.

3˙3. *The Centaurus region.* – As stated previously, both for the blind search and the catalog-based search, the main driving force for anisotropies was the presence of a hotspot of events in the Centaurus region. This portion of the sky contains the Centaurus A/M83 group, with the closest radiogalaxy to the Milky Way, Centaurus A, and the two starburst galaxies M83 and NGC4945. For this reason, this region has always been the target of searches by the collaboration, and this work updates these searches.

The analysis was performed in a similar way to the blind search, centering the target to the position of Centaurus A rather than looking at the whole sky. The obtained p-value was penalized similarly. The most significant excess was found at the threshold energy 41 EeV and $\Psi = 27°$, with an excess of 56 events over isotropy. The post-trial p-value obtained was 4.5×10^{-5}, similar to the result for starburst galaxies in the catalog-based search (fig. 2).

4. – Conclusions

This contribution presented the definitive results on the anisotropies in the arrival directions of UHECRs detected at the Pierre Auger Observatory during its first phase.

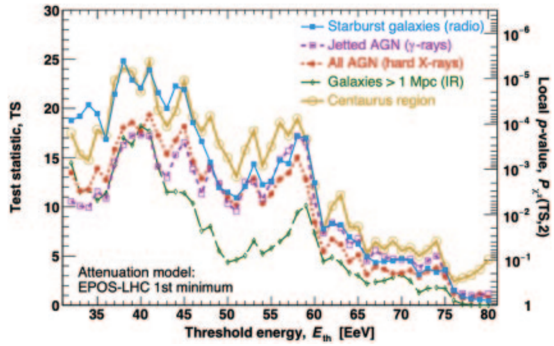

Fig. 2. – Test statistic as a function of the threshold energy for the four studied catalogs. Also shown as a golden line is the local p-value, penalized only for the scan in search radius, for the overdensity search in the Centaurus region.

No indication of significant anisotropies emerged from a blind search conducted on the whole portion of the sky visible by the Observatory. This result can be attributed to the relatively small size of the dataset compared to the complexity of the parameter space. More complex analyses that take into account UHECR attenuation and local distribution of matter disfavor isotropy at the 3–4σ level depending on the considered catalog. Lunardini19, 2MASS, Swift-BAT105 and 3FHL catalogs are all approximately equally favored with a $\sim$10% flux excess. This similarity is driven by the main hotspot in the data, a cluster of events in the Centaurus region; the most favoured catalog, which includes starburst galaxies traced by radio observations, correctly models a secondary hotspot in the southern galactic pole that other catalogs miss. A model-independent analysis of the Centaurus region shows an excess of events with significance greater than 4σ. At this point, it is not possible to point with certainty the sources of UHECRs; the main challenge remains to disentangle the effects of the magnetic fields that deflect particles in their travel to Earth. A reduction of this effect is obtainable by picking out only the lightest component from the dataset, and Auger Prime is designed to do so.

A full paper on the analyses presented in this work and more is in preparation by the Pierre Auger Collaboration.

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