IL NUOVO CIMENTO **43 C** (2020) 22
DOI 10.1393/ncc/i2020-20022-7

Colloquia: IFAE 2019

Anisotropies in the highest-energy cosmic rays with data from the Pierre Auger Observatory

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received 8 June 2020

Summary. — After 15 years of operations, the Pierre Auger Observatory has gathered more data on the highest-energy cosmic rays than any other experiment in the past. With this data, new light has been shed on the origin of such high-energy particles, albeit no final word on their sources has been said yet.

1. – Introduction

Cosmic rays have been known for more than a hundred years now, and they have unveiled their astonishing high energies in the last 50 years. While recently we have enormously increased our knowledge about these particles, the exact nature of the sources of the highest-energy cosmic rays, up to some 10^{20} eV(1), remains unknown.

The observation of ultra-high-energy cosmic rays (UHECR) is not made directly, but through the cascades of billions of particles that are created when the primary cosmic ray hits an atom of the atmosphere. By studying the characteristics of these Extensive Air Showers (EAS), we can extract information on the arrival direction of the primary cosmic ray, on its energy and on its nature, in order of increasing difficulty of the measurement. Since cosmic rays are charged particles, they are deflected by magnetic fields, not pointing directly at their sources. So, a thorough study of their arrival directions is needed to extract information on their origin, and different scenarios need to be taken into account.

2. – The Pierre Auger Observatory

The Pierre Auger Observatory [1], located near Malargue (province of Mendoza, Argentina) detects cosmic rays by studying the EAS they induce in the atmosphere. It consists of an array of over 1600 water Surface Detectors (SD) each with 3 PMTs and a FADC to observe the Cherenkov light produced by particles, deployed over a triangular

(1) Or ∼100 EeV, since 1 EeV = 10^{18} eV.

grid of 1.5 km spacing and covering an area of 3000 km^2. The ground array is overlooked by 27 fluorescence telescopes, grouped in four sites, making up the fluorescence detector (FD). Whereas the SD samples the secondary particles at the ground, the FD observes the longitudinal development of the shower in the atmosphere (*i.e.*, the energy deposit as a function of the atmospheric depth) by detecting the fluorescence light emitted by excited nitrogen molecules and the Cherenkov light induced by shower particles in air. Using FD, the electromagnetic energy released by the shower in the atmosphere can be measured from the integral of the longitudinal profile and the total energy of the primary particle is then derived by correcting for the invisible energy carried by muons and neutrinos. Thus the FD provides a calorimetric measurement of the primary energy, in a way that is practically independent of the primary type and of the details of the hadronic interaction models. Moreover, it can directly measure the depth of the shower maximum (X_{MAX}) which is a powerful mass discriminating variable. However, unlike the SD array, the FD may only operate during clear and moonless nights and thus with a duty cycle reduced to about 13%. The FD is then used to *calibrate* the energy measured by SD alone: this way we assure a good energy estimation (∼15% resolution) with the surface detector that has a duty cycle of nearly 100%. All the anisotropy results presented in the following are based on SD data.

The study of anisotropies in the arrival direction distribution of UHECRs as measured by Auger can be divided into two main categories:

- *Small/intermediate-scale anisotropies.* At energies above few tens of EeV ($\sim 10^{19}$ eV), cosmic rays are expected to begin to interact with the photon backgrounds, in particular the cosmic microwave one, thus losing their energy. This means that cosmic rays at these energies are limited to come within a horizon of few hundreds of Mpc, and this limits the number of candidate sources, facilitating the search for correlations. Moreover, the higher the energy the lower a cosmic ray is deflected by the magnetic field, so only at these energies deflections are small enough (at least for light cosmic rays such as protons) to expect a correlation between the arrival direction of the cosmic ray and the position of a source. The downside of the analysis at these energies is that only a few hundred events are available, since the cosmic ray spectrum is quite steep.

- *Large-scale anisotropies.* At lower energies, of the order of 1 EeV, cosmic rays are much more deflected by magnetic fields and thus cannot be used to trace back to their sources. However, a large-scale structure can still be present, that can give us information on the distribution of the sources. Thanks to the large number of events available at these energies (tens to hundreds of thousands), even small anisotropies can be detected in Auger data. The most challenging aspect of such studies is the need of having a very precise control on the uncertainties on the flux and on the exposures, to be sure that any anisotropy effect found cannot be caused by detector effects (*e.g.*, weather condition affecting the detector efficiency on a day/night regular basis).

3. – Small/intermediate-scale anisotropies

Regarding the search for small and intermediate-scale correlation at high energies (above $\sim 10^{19}$ eV), no observation has been made so far. However, a few interesting indications of anisotropy have been found. First of all, the region around Centaurus A, the closest active galaxy, shows an excess of UHECR with energy greater than 37 EeV

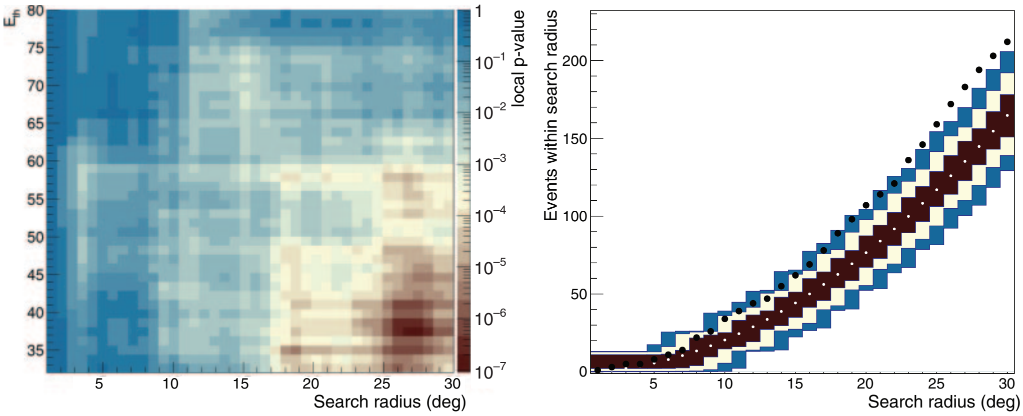

Fig. 1. – Left: local p-value when searching for excesses around the position of Centaurus A, as a function of search radius and energy threshold. Right: the comparison of number of events with $E > 37\,\text{EeV}$ within a certain angle from CenA (black dots) compared to the expectation from a isotropic distribution of UHECRs (white dots) and its 1, 2 and 3 σ dispersion (red, cream and blue, respectively). From [2].

observed up to August 2018. Inside a circle of radius $\psi = 28°$ centered on CenA 203 events were observed while 141 were expected, and the local significance is 5.1 σ. This significance has to be penalized because we performed a scan on the energy threshold and angular scale of the excess, leading to a one-sided post-trial significance of 3.9 σ [2]. This excess is steadily growing from earlier publications, such as [3], where only events up to March 2014 were considered. In fig. 1 the p-value at different angular search radius and different energy scales is shown.

An even more significant departure from isotropy was found when searching correlation with catalogs of candidate sources, taking into account also their luminosity, under the assumption that the UHECR flux is proportional to the non-thermal electromagnetic flux. The search was performed through a maximum likelihood method that took into account also the absorption due to the interaction of UHECRs during their propagation from each source. Two parameters were left free in this analysis: the smearing angle θ and the fraction of anisotropic events f_{aniso}(2). The analysis was repeated by varying the energy threshold of the selected events between 32 and 80 EeV in steps of 1 EeV. The likelihood analysis was performed on 4 catalogs: first, the 2MRS [4], taking out sources closer than 1 Mpc, as selected in [5], which traces the nearby matter. Secondly, the AGNs observed by the BAT camera on the Swift satellite [6], which includes both radio loud and quiet AGNs. Then γ-AGNs, selected from the 3FHL catalog [7] were used. Finally, the last catalog used is a sample of starburst galaxies selected based on their continuum emission at 1.4 GHz, used as a proxy of their UHECR flux (see [5] for further details), with the addition of the Circinus Galaxy and sources selected with HEASARC Radio Master Catalog(3). The number of sources selected this way is 32. The maximum likelihood-ratio is found with starburst galaxies for $E > 38\,\text{EeV}$, with a test statistics of 29.5. At

(2) Meaning that we assume that a large fraction of events is isotropic, either because they are isotropized by magnetic fields or because they are coming from a number of distant, faint sources.
(3) `https://heasarc.nasa.gov/W3Browse/master-catalog/radio.html`.

TABLE I. – *Values of the parameters that maximize the likelihood-ratio test against isotropy for the four different models as described in the text. From* [2].

Catalog	$E_{\rm th}$	TS	Local p-value	post-trial	$f_{\rm aniso}$	θ
Starburst	38 EeV	29.5	4×10^{-7}	4.5 σ	$11^{+5}_{-4}\%$	$15^{+5}_{-4}{}^{\circ}$
γ-AGN	39 EeV	17.8	1×10^{-4}	3.1 σ	$6^{+4}_{-3}\%$	$14^{+6}_{-4}{}^{\circ}$
Swift-BAT	38 EeV	22.2	2×10^{-5}	3.7 σ	$8^{+4}_{-3}\%$	$15^{+6}_{-4}{}^{\circ}$
2MRS	40 EeV	22.0	2×10^{-5}	3.7 σ	$19^{+10}_{-7}\%$	$15^{+7}_{-4}{}^{\circ}$

this energy threshold, the best-fit parameters are $f_{\rm aniso} = 11^{+5}_{-4}\%$ and $\theta = 15^{+5}_{-4}{}^{\circ}$, corresponding to a local p-value of 4×10^{-7}, which has then to be penalized for the scan on energy threshold, obtaining a post-trial significance of 4.5 σ. A summary of the best-fit parameters obtained for all the four catalogs is reported in table I.

3˙1. *Correlation with high-energy neutrinos.* – A search for spatial correlation similar to what is done with astrophyiscal catalogues can be done also with high-energy neutrinos. These particles are expected to be produced in the same sites as ultra-high-energy cosmic rays, but have the advantage of propagating without being deflected by magnetic fields. The Pierre Auger Collaboration, together with Telescope Array, a UHECR detector in the Northern Hemisphere, has participated to a joint effort with the two largest neutrino telescopes: ANTARES and IceCube. We searched for correlation between the highest energy cosmic rays and neutrinos both from the high-energy sample (dominated by astrophysical neutrinos but with low statistics) and from the point source sample (dominated by atmospheric neutrinos but with large statistics). None of these efforts lead to a significant result, and even the hint of correlation that were suggested by early analyses [8] have now grown to be compatible with isotropic expectation [9]. This however is not unexpected, since neutrinos do not have a limit on propagation distance as UHECR do and the neutrinos measured by current neutrino telescopes have energies too small to be the product of the interaction of a $\sim 10^{19-20}$ eV cosmic ray in the vicinity of its source. A large fraction of them might then come from sources which are capable of accelerating cosmic rays only to lower energies than the one considered in this study.

4. – Large-scale anisotropies

The study of large-scale anisotropies can give useful information on the distribution of the sources even in case of strong magnetic fields because anisotropy cannot arise through deflections of an originally isotropic flux by a magnetic field, following Liouville's theorem. So, any anisotropy found in data must be a residual of the original anisotropy in the distribution of the sources, partly diminished by the effect of magnetic fields.

The Pierre Auger Observatory observed with high significance a large-scale anisotropy [10] for the events with energy greater than 8 EeV. In this energy range, the amplitude of the first harmonic was found to be $\sim 6\%$ and incompatible with an isotropic distribution at more than 5.2 σ level. For these events, an extragalactic origin

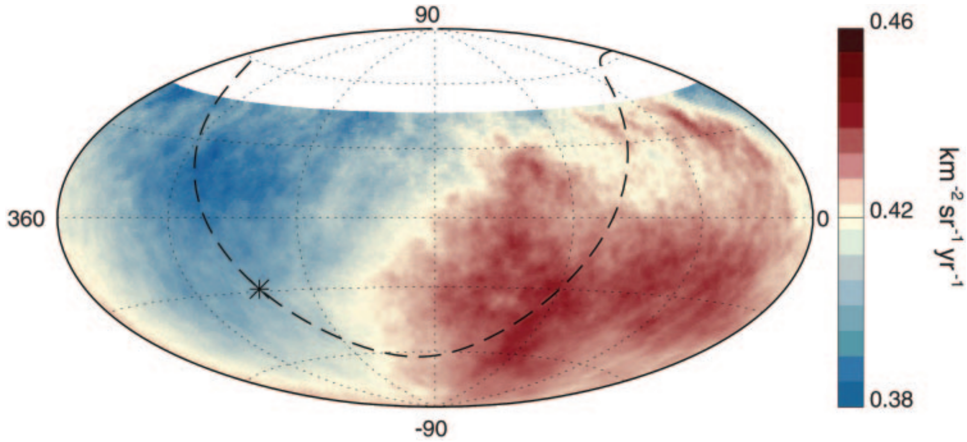

Fig. 2. – The distribution of the arrival direction of cosmic rays in equatorial coordinates, smoothed with a 45° top-hat function. The Galactic center is indicated by an asterisk, the Galactic plane by a dashed line. From [10].

of UHECR is favored since the dipole direction is not compatible with what would be expected from a Galactic origin (the dipole direction points ∼125° away from the Galactic center), even taking into account the largest deflection allowed by the current Galactic magnetic field measurements. The distribution of cosmic rays at these energies is shown in fig. 2. The same analysis on events in the 4–8 EeV energy range lead, on the other hand, to a result compatible with isotropy within uncertainties. If the sources of UHECRs in this energy bin were galactic, we would expect to see anisotropy, and only in the case of a heavy composition one could expect this anisotropy to be suppressed by magnetic fields to the point of being undetectable. Since composition measurements made by Auger favor light primaries at these energies, also for this energy bin an extragalactic origin of UHECR is favored by our data.

Further analyses have been performed in an extended energy range [11], showing that the amplitude of the dipole grows with energy above 8 EeV, reaching ∼16% above 32 EeV. At lower energies the amplitude decreases and below 1 EeV the phases mostly point near the Galactic center direction although the amplitudes are not significant. This may suggest that the transition between Galactic and extra-galactic components may happen between 1 and few EeV.

5. – Conclusions

The quest for the sources of ultra-high-energy cosmic rays has reached some important milestones in the past few years, in particular thanks to the data collected by the Pierre Auger Observatory. To finally identify the sources, a higher statistics will help, possibly aided by an event-by-event estimate of the UHECR composition at the highest energies. This would allow us to perform analyses like the ones presented in this proceedings only on the *light* component, if present, which is the least deflected. To achieve this goal, the Pierre Auger Observatory is now undergoing an upgrade, Auger Prime [12]: with this enhancement, new light will be shed on the origin of the Universe's most energetic particles.

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