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Arrival directions of UHECRs after the end of phase 1 of the Pierre Auger Observatory

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Summary. — The Pierre Auger Observatory is the largest and most important hybrid detector designed to investigate the origin and the nature of Ultra High Energy Cosmic Rays. The observatory has been continuously operated since 2004, and has achieved a total detection exposure of approximately 122000 $\mathrm{km^2\,sr\,yr}$. During over 18 years of research, the Auger Observatory has collected a huge amount of high-quality data, which gave us knowledge about the origin of the most energetic particles ever observed in the universe. This contribution will present the main and most recent results of the arrival direction studies obtained with the Auger phase 1 dataset, *i.e.*, the one before the installation of the upgrade Auger Prime, currently under completion. These include the searches for possible sources from small to large scale: studies of dipolar and multipolar anisotropies, the search for excesses of the order of the scale of tens of degrees at the highest energies, and the search for excesses of the order of the angular resolution ($\sim 1^\circ$) to look for neutral particles.

1. – Introduction

Cosmic rays are the most energetic known particles in the universe. This radiation, formed by protons, electrons, positrons, and atomic nuclei, is accelerated by astrophysical sources of various kinds up to the most extreme energies ever observed, of the order of 10^{20} eV. Studying the origins and characteristics of Ultra High Energy Cosmic Rays can provide insights into some of the most powerful phenomena and particle emission sources in the cosmos.

Although UHECRs appear to arrive mostly evenly from all directions in the sky, this does not necessarily mean that their sources are isotropically distributed around

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us: as charged particles are deflected and scattered by magnetic fields, they lose information about their original arrival direction. Despite this difficulty, several research techniques have been developed and used, during the 16 years of phase 1 of the Pierre Auger Observatory, to identify the origin of UHECRs. At low energy, around a few EeV ($1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV}$), the CRs sources cannot be searched for directly, due to too large cosmic-ray deflections. In this regime, the search for large-scale anisotropy was carried out. At higher energy, $\approx$tens of EeV, the distribution of the UHECRs arrival directions might show anisotropy at smaller angular scales, mirroring the inhomogeneous distribution of the nearby extragalactic matter. With the Pierre Auger Observatory data, an alternative approach was also considered for anisotropies studies: charged cosmic rays can produce, in interactions with background radiation (CMB, dust, photons), neutral particles which, if recognized and with some caveats, can become interesting messengers.

2. – The Pierre Auger Observatory phase 1

The Pierre Auger Observatory, located in a vast table land in the southern hemisphere in the province of Mendoza, Argentina, is the largest cosmic ray observatory ever built. Designed as a pioneering hybrid detection facility, the observatory is composed of two complementary detectors: an array of 1660 surface stations, Water Čherenkov detectors, covering an area of $3000\,\mathrm{km}^2$, which constitutes the surface detector (SD), and 27 fluorescence detector telescopes (FD) that, located at 5 sites around the SD grid, look at the atmosphere above. Both SD and FD detect UHECRs indirectly by measuring respectively the front at ground level and the longitudinal development in the atmosphere of the showers of secondary particles that are produced by the interaction of the primary cosmic rays with molecules in the atmosphere. The Observatory has been active continuously since 2004, and in 2020, at the end of phase 1 before the upgrade called Auger Prime, in an advanced stage of deployment at the time of writing, it achieved a total detection exposure of approximately $120000\,\mathrm{km}^2\mathrm{sr\,yr}$. The results of arrival direction analyses presented are the main obtained with Auger data during phase 1.

3. – Analysis of arrival directions of UHECRs

3$\cdot$1. *Large-scale anisotropies.* – The data recorded at the Pierre Auger Observatory up to 31/12/2020, with a total exposure of about $110000\,\mathrm{km}^2\mathrm{sr\,yr}$, were analyzed for the search for large scale anisotropies [1]. The selected events, in the field of view with declination between $-90°$ and $+45°$ (covering 85% of the sky), were divided into two energy ranges, $4\,\mathrm{EeV} < E < 8\,\mathrm{EeV}$ and $E \geq 8\,\mathrm{EeV}$, and for these energies the deflections due to magnetic fields are not negligible and excesses can only be sought on large angular scales. To search for this type of anisotropy, a Rayleigh first-harmonic analysis of the counting rate of events, both in right ascension α and in azimuth angle ϕ, which is sensitive to non-uniformity in declination of the reconstructed arrival directions, was carried out. The combination of these two harmonic analyses made it possible to be sensitive to anisotropies with three-dimensional dipole structures, such as those sought in this case. At energies below 8 EeV, no significant result was observed, whereas, at energies above 8 EeV, the total dipole amplitude is $d = 7.3^{+0.011}_{-0.009}\%$, with a level of significance more than the 6.6σ. This dipole anisotropy points to the $(\alpha_d,\, \delta_d) = (+100°,\, -24°)$ direction, about 115° from the Galactic Center, which gives a clear proof of extragalactic origin of the majority of UHECRs for energies higher than 8 EeV.

3˙2. *Medium scale anisotropies.* – The search for anisotropies on medium angular scales is feasible for the higher energies of UHECRs, typically in the order of tens of eV, whose deflections should be small, requiring however that the CR have a small charge [2]. Moreover, the region of the local universe that can be investigated in the search for sources of higher energy UHECRs is limited by the GZK effect, *i.e.*, the interaction of the primary cosmic rays with the cosmic microwave background photons [3]. The final dataset used in the research of medium scale anisotropies contains 2625 events collected during phase 1 by SD with $E > 32\,\mathrm{EeV}$.

3˙2.1. Blind search for overdensities. Considering the entire portion of the sky visible from the observatory, the number of events observed within a given angular window was compared to the number of events expected from an isotropic background. A variety of search radii, between 1° and 30° and energy thresholds between 32 EeV and 80 EeV were examined. The most significant excess, with a local p-value of 1.3×10^{-7} and a post trial p-value of 3%, was found in the Centaurus region, centered on equatorial coordinates (α, δ) = (+196.3°, −46°.6) with a radius of 24° and an energy threshold of 41 EeV.

3˙2.2. Catalog-based searches. Four catalogs of possible sources of UHECRs were selected for this analysis(1): 2MASS, which traces all galaxies in infrared; Swift-BAT 105 months, which includes all active galactic nuclei (AGN) in hard X-ray; Fermi-3FHL, which includes jetted AGNs in gamma-rays; and Lunardini-19, which includes Starburst Galaxies on radio. The analysis was performed by cross-correlating the observed UHECRs flux with catalogs, and for each of them the statistical test TS was calculated. All catalogs have shown their most significant signal at $E \geq 38$–$41\,\mathrm{EeV}$, and an angular scale between 23° and 27°. The most promising catalog turned out to be that of the Starbursts Galaxes with a significance of 4σ.

3˙2.3. Search in the Centaurus region. In the light of the results of the analyses described above, the Centaurus region, identified as a promising hotspot since the first researches of anisotropies carried out by the Pierre Auger Collaboration, has been investigated in more detail. In fact, in addition to the hint given by the blind search, the correlation analysis with the catalogs highlighted the presence of the two most significant Galaxies in this area. The Centaurus area was then investigated with a method similar to the one used for the blind analysis, and a 3.9σ post-trial significance for threshold energy of 38 EeV and search radius equal to 27° was found.

3˙3. *Neutral particles.* – A different research approach was also followed with the Auger phase 1 datasets: charged cosmic rays can —in interactions with background radiation (photons, dust, CMB)— produce neutral particles, which can be used as interesting messengers to identify sources of UHECRs and to investigate the emissivity and cosmological evolution of the acceleration sites.

Neutrinos of energies of about 1/20 of the primary cosmic ray's energy can be produced in interactions of UHE protons with CMB. Neutrinos are sought after by searching deep down-going inclined shower with a considerable e.m. component, sensible to all flavors, or up-going earth-skimming showers to recognize tau flavored neutrinos. Despite the large exposure of phase 1, no traces attributable to UHE neutrinos were observed. However, this lack of observation has provided an opportunity to establish stringent lim-

(1) For details on the catalogs see the reference and description in [2].

its on the theoretical models for the production of cosmogenic neutrinos [4], according to which the flux of UHECRs at the highest energies is dominated by protons.

UHEγ can be generated by cosmic rays by interaction with CMB, by pion photoproduction, or nuclear collisions near CRs sources. The study of their flux can be used to identify sources, by correlation with catalogues, or interpreted to search for signature of top down models for UHECRs production. Showers induced by UHEγ have not yet been identified with good certainty, then upper bounds to the photon flux have been placed, strongly disfavoring exotic scenarios which describe ultra high energy cosmic rays as produced by the decay of unknown supermassive particles [5].

UHECRs can produce also *UHE neutrons* in interactions in proximity to their source, as in pion photo-production and nuclear interactions. Neutrons, despite producing showers indistinguishable from those of protons, can be used to search for sources of UHECRs on angular scales of less than 1°. An excess of particles at this scale coming from a very specific direction in the sky may be solely due to the neutral component of cosmic rays. A free neutron, however, is subject to decay and at the Auger detection energies make possible to search for sources only within our Galaxy. The Auger Collaboration carried out two analyses of neutrons fluxes: a blind search [6] and a search for correlation with Galactic catalogs [7]. Both analyses allowed us to place interesting upper limits on the flux of neutrons originating in our Galaxy, in particular the one attributable to the Galactic Center and Plane.

4. – Conclusions

The upgrade Auger Prime of the Pierre Auger Observatory's detector is nearing completion. The start of its deployment ended Auger phase 1, which lasted from 2004 to 2020 during which several efforts were made to study anisotropies in the arrival directions of the detected UHECRs, in an attempt to identify acceleration sites.

The field of view of the observatory was investigated following complementary analyses, from large to small angular scales. The main results led to identify a 6.6σ significant dipole anisotropy 115° distant from the Galactic Center for events with energy greater than 8 EeV, which suggest the mainly extragalactic origin of UHECRs for these energies. The analyses on medium angular scale and at the highest energies have identified an interesting hotspot in the Centaurus region, to be better investigated in the future with the ever increasing exposure of the observatory. The photons, neutrinos and neutrons fluxes, produced by the charged primary cosmic rays near their source, were studied on a small angular scale: limits on their fluxes have been set, which led to stringent constraints against exotic models to explain the production of UHECRs, and possible sources in our Galaxy have been investigated. Starting from these results, future researches with Auger Prime will be hopefully able to help shed more light on the origin of UHECRs.

REFERENCES

[1] The Pierre Auger Collaboration, in *Proceedings of the ICRC2021, International Cosmic Ray Conference (ICRC2021), Berlin (Germany), July 2021* (PoS, SISSA) 2021.
[2] The Pierre Auger Collaboration, *Astrophys. J.*, **935** (2022) 170.
[3] Zatsepin G. T. and Kuz'min V. A., *J. Exp. Theor. Phys. Lett.*, **4** (1966) 78.
[4] The Pierre Auger Collaboration, *JCAP*, **10** (2019) 022.
[5] The Pierre Auger Collaboration, *Astrophys. J.*, **933** (2022) 125.
[6] The Pierre Auger Collaboration, *Astrophys. J. Lett.*, **760** (2012) 148.
[7] The Pierre Auger Collaboration, *Astrophys. J. Lett.*, **789** (2014) L34.