The Pierre Auger Observatory status and latest results

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Abstract. The Pierre Auger Observatory, in Argentina, is the present flagship experiment studying ultrahigh-energy cosmic rays (UHECRs). Facing the challenge due to low cosmic-ray flux at the highest energies, the Observatory has been taking data for more than a decade, reaching an exposure of over 50 000 km^2 sr yr. The combination of a large surface detector array and fluorescence telescopes provides a substantial improvement in energy calibration and extensive air shower measurements, resulting in data of unprecedented quality. Moreover, the installation of a denser subarray has allowed extending the sensitivity to lower energies. Altogether, this contributes to provide important information on key questions in the UHECR field in the energy range from 0.1 EeV up to 100 EeV. A review of main results from the Pierre Auger Observatory is presented with a particular focus on the energy spectrum measurements, the mass composition studies, the arrival directions analyses, the search for neutral cosmic messengers, and the investigation of high-energy hadronic interactions. Despite this large amount of valuable results, the understanding of the nature of UHECRs and of their origin remains an open science case that the Auger collaboration is planning to address with the AugerPrime project to upgrade the Observatory.

1 Introduction

The nature and the origin of ultrahigh-energy cosmic rays are still enshrouded in mystery, even if in last decade measurements have shed light on these puzzling questions. UHECRs are very scarce and their characteristics are inferred from the measurement of extensive air showers (EASs) they produce. The Pierre Auger Observatory [1] located in the province of Mendoza (Argentina) and covering 3000 square kilometres, brings unique capabilities to the UHECR study. It combines two techniques to measure the EAS properties by observing their longitudinal development in the atmosphere as well as their lateral spread at ground level. Charged particles and photons that reach the ground are detected with the surface detector (SD) consisting of 1660 autonomously operated water-Cherenkov detectors (WCDs). The WCDs are arranged on a triangular grid of 1500 m spacing, except for a denser infill area of $\sim$ 30 km^2, where the spacing is 750 m. The surface detector operates 24 hours per day, and provides a huge collecting area. The atmosphere above the SD is observed by the fluorescence detector (FD) which consists of 27 fluorescence telescopes to detect the faint UV light emitted by nitrogen molecules excited by the charged particles from the EAS. The field of view (FoV) of each

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telescope is 30° in azimuth, and 1.5 − 30° in elevation, except for three of them, the High Elevation Auger Telescopes (HEAT), whose FoV is 30 − 60° in elevation, allowing the observation of nearby low-energy showers above the denser infill area. The FD can only operate during dark, moonless nights with a field of view free of clouds (duty cycle ∼15%). On-line and long-term performances of the detectors and data quality are monitored continuously, and a set of high-quality devices installed in the Observatory array monitor the atmospheric conditions during operation [2]. A 17 km^2 sub-array of 153 radio sensors (Auger Engineering Radio Array) is dedicated to EAS radio detection. The progresses made in this detection technique in particular to identify mass-sensitive radio parameters are reported elsewhere in these proceedings [3].

High-quality data have been collected continuously for about ten years, with a SD annual exposure of ∼5500 km^2 sr yr. The longitudinal profile reconstructed by the FD is providing a nearly calorimetric measurement of the primary energy, with total systematic uncertainty of 14% [4]. From the shower lateral distribution reconstructed using the WCD signals, a SD energy estimator is inferred. A high-quality subset of hybrid events recorded by both the SD and the FD is used to calibrate the SD energy estimator with the FD energy measurement, hence providing an almost model-independent energy calibration.

2 Spectrum measurements

The UHECR spectrum is obtained from four different datasets [5], corresponding to an exposure now larger than 50000 km^2 sr yr. Data from the SD-750 m allow measurements down to 10^{17} eV; SD-1500 m vertical data (i.e. zenith angle < 60°) are covering the range from the full trigger efficiency energy threshold of $3 \cdot 10^{18}$ eV up to the highest energies; SD-1500 m horizontal events contribute above $4 \cdot 10^{18}$ eV; hybrid data cover the range between 10^{18}eV and $10^{19.6}$ eV. The four measurements are combined taking into account the systematic uncertainties of the individual measurements. The

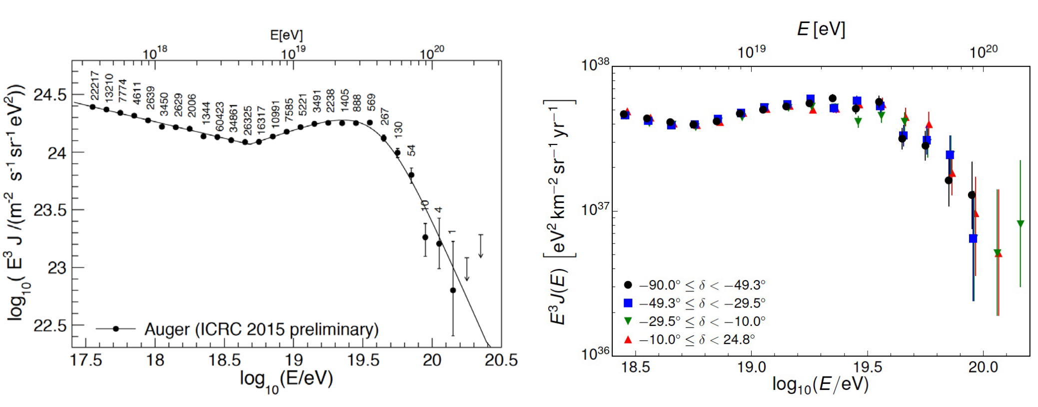

Figure 1. Cosmic-ray energy spectrum measured by Auger ([5]) - Left: from combining four independent measurements (see text) - Right: in four declination bands, using SD-1500 vertical event.

resulting spectrum (Fig. 1-left) flattens from a power law with index (3.29 ± 0.02(stat) ± 0.05(sys)) to one with index (2.60 ± 0.02(stat) ± 0.1(sys)) at E_{ankle} = 4.8 ± 0.1 ± 0.8 EeV. A clear suppression is observed at a significance in excess of 20σ beyond E_s = 42.1 ± 1.7 ± 7.6 EeV, the energy at which the differential flux is reduced to one-half of that expected from the extrapolation of the power law above the ankle. The large number of events and the wide range of declinations δ from −90° to +25°, allow the study of the UHECR flux as a function of δ. Fig. 1-right shows the four spectra obtained with events separated into four declination bands of roughly equal exposure. The agreement between the spectra is within 5% below E_s and 13% above, therefore there is no indication of a δ-dependent flux.

3 Mass composition studies

The most robust observable sensitive to the mass of the primary particle is X_{max}, the depth of maximum of the shower development, directly measured from the longitudinal profile reconstructed with the FD. The most recent analysis includes the data of HEAT, allowing measurement from 0.1 EeV [6], as shown in Fig. 2. Up to 2 EeV the increase of $\langle X_{max}\rangle$ is larger than the one expected for a constant mass composition (see proton/iron simulations), indicating that the mean primary mass is getting lighter. Around $\simeq$ 2 EeV the elongation rate becomes significantly smaller, then the composition is becoming

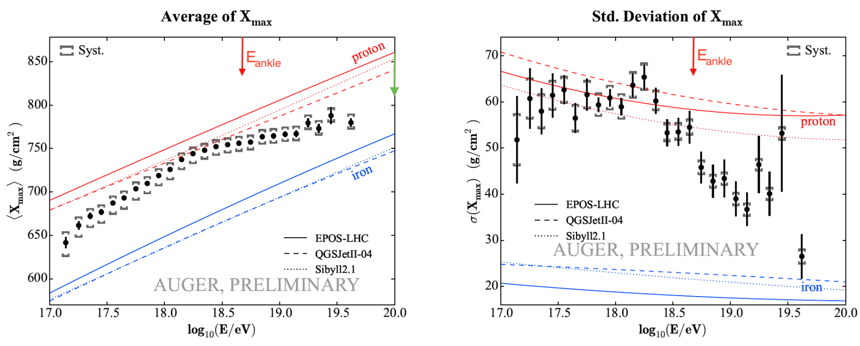

Figure 2. The mean (left) and the standard deviation (right) of the measured X_{max} distributions as a function of energy compared to air-shower simulations for proton and iron primaries.

heavier. The fluctuations of X_{max} start to decrease at around the same energy, confirming the previous observations. These measurements can be interpreted by converting them to $\langle$lnA$\rangle$ [7], with A the atomic mass number, based on simulations using current hadronic interaction models EPOS-LHC [9] and QGSJetII-04 [8]. For both models similar trends with energy are observed for the mean and the variance of lnA. The primary mass is decreasing up to $\simeq$ 2 EeV, the spread of the masses being almost constant: several components are expected, evolving from intermediate to light mass. $\langle$lnA$\rangle$ is increasing at the higher energies, the variance showing a decrease: fewer components are expected, with mass evolving from light to heavy. These behaviours might be an indication that the relative fraction of protons becomes smaller for energies above 2 EeV. The distributions of X_{max} were also interpreted in terms of primary masses [10] based on the QGSJetII-04, Sibyll 2.1 [11] and EPOS-LHC hadronic interaction models. The results suggest also a mixed composition. Around the ankle, a very light composition consisting of proton and Helium only is favoured using QGSJetII-04 and Sibyll 2.1, while for EPOS-LHC, intermediate nuclei (from CNO group) contribute. To get a more direct and robust estimation of the spread of masses in the primary beam, relying less on interaction models, the correlation between X_{max} and S(1000) is studied, where S(1000) is the signal at 1000 m from the shower core, reconstructed with the SD. For single nuclear components this correlation is expected to be $\gtrsim 0$, although for mixed composition, the correlation is negative. For hybrid events with energies of $\log_{10}$(E/eV) = 18.5 – 19.0 and zenith angles $< 65°$ a significant negative correlation was found consistent with a spread of masses σ(lnA) > 1, meaning the composition around the ankle is actually mixed [12]. The hypothesis that below 3 EeV, a fraction of protons mainly of extragalactic origin is dominant and that the ankle corresponds to the proton energy loss through e^+e^- pair production in interactions with the cosmic microwave background (CMB) is then disfavoured.

By simultaneously fitting the spectrum and the X_{max} evolution above 5 EeV, the Auger results can be interpreted assuming a simple astrophysical scenario, as reported elsewhere in these conference proceedings. The best fit supports the hypothesis of a flux suppression partly due to the reach of the source maximum energy, while the second local minimum corresponds to a scenario where the suppression is due to propagation effects (Greisen, Zatsepin and Kuz'min, or GZK cutoff) [13].

4 Neutral cosmic messengers

Both neutrinos and photons are sought for in the flux of UHECRs detected by Auger. The neutrino search is performed by studying very inclined showers and earth-skimming ones [14]. The criteria are based on the characteristics expected for "young" showers initiated by neutrinos, developing deep in the atmosphere, compared to "old" ones from inclined hadronic showers, having their electromagnetic component fully absorbed before reaching the detectors. Photon showers, due to their slower devel-

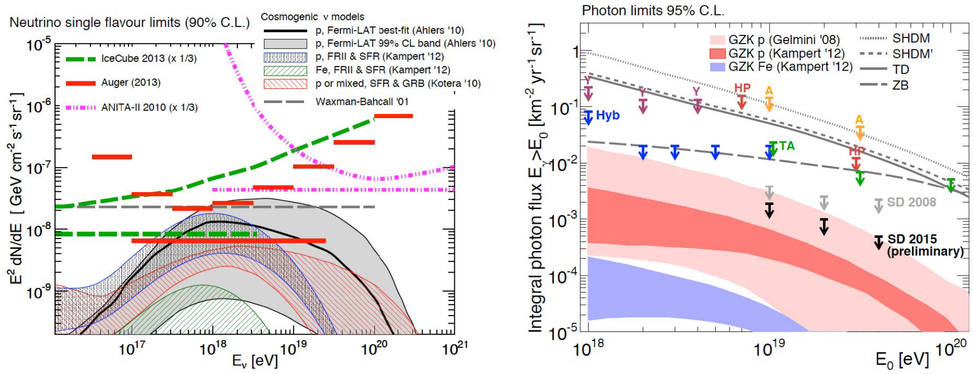

Figure 3. Left: neutrino flux upper limits (at 90% C.L.), in integrated (horizontal lines) and differential forms (see [14] for details). - Right : photon flux upper limits (95% C.L.) (see [15] for details).

opment and the dominance of the electromagnetic component can be distinguished from hadronic showers [15]. SD events on the one hand, and hybrid events on the other hand have been analyzed, to cover the energy range above 1 EeV. Assuming a differential flux $dN(E) = k \cdot E^{-2}$ for both neutrinos and photons, stringent upper limits to their flux are derived. The Auger limits on neutrinos (Fig. 3-left) outperform those from IceCube and ANITA, and also the Waxman-Bahcall limit; in the range $10^{17} - 10^{19}$ eV they are challenging the contribution from cosmogenic-neutrino models. The limits to the integral photon flux are shown in Fig. 3-right. The obtained limits are the most stringent for $E > 10$ EeV and start to constrain the most optimistic predictions of cosmogenic photon fluxes under the assumption of a pure proton composition.

5 Anisotropy searches

The distribution of the arrival directions of ultrahigh-energy cosmic rays is also scrutinised, complementary to the spectrum and mass measurements, to shed light on their origin and nature. The presence of anisotropies is searched for at small and intermediate angular scales [16] in the distribution of arrival directions of the most energetic cosmic rays above a few tens of EeV, where the magnetic deflections (at least of those with a small charge) may be only a few degrees. Different methods are employed: search for autocorrelation by looking for pairs of events, blind search for localized excesses of events (Fig. 4-left), search for correlations with specific sky regions (galactic center, galactic and super-galactic planes) and with sources from catalogues (2MRS galaxies, Swift-BAT AGNs, ...). The performed tests on the UHECR arrival distribution point out a high degree of

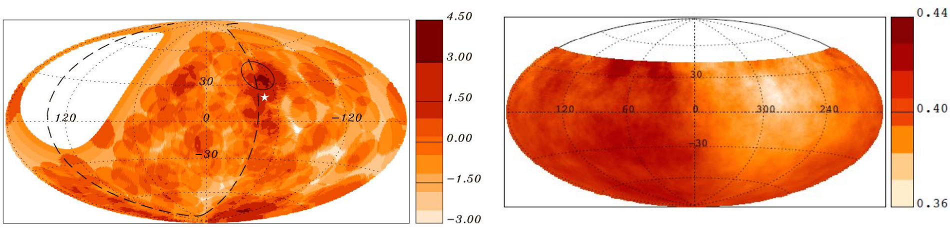

Figure 4. Left: Li-Ma significance map (galactic coordinates) of overdensities in 12°−radius windows for the events with E> 54 EeV. Right: sky map (equatorial coordinates) of flux in km^{-2} yr^{-1} sr^{-1} smoothed in angular windows of 45° for E> 8 EeV.

isotropy, jeopardising the initial expectation of few sources and light primaries.

Large-scale anisotropies could signify a galactic−extragalactic transition which may entail a significant change in the arrival direction distribution. The partial sky coverage limits the harmonic expansion of the cosmic-ray flux distribution, but the large amount of data accumulated by the Pierre Auger Observatory are well-suited to search for dipolar and quadrupolar patterns, from 10 PeV to the highest energies (Fig. 4-left). In the energy band $E > 8$ EeV a dipole component with amplitude $7.3 \pm 1.5\% (p = 6.4 \times 10^{-5})$, pointing to $(\alpha, \delta) = (95° \pm 13°\ , -39° \pm 13°)$ is found, above isotropic expectations [17].

6 Investigation of high-energy hadronic interactions

The UHECR studies provide a means of investigating hadronic interactions at energies far beyond the reach of the LHC. With Auger hybrid data, using the tail of the X_{max} distribution, the determination of the cross-section of proton-air collisions is achieved in the two energy intervals in $\log_{10}$(E/eV) from 17.8 to 18 and from 18 to 18.5 [18]. Another approach to investigate high-energy hadronic interactions and to compare measurements to models is to consider the muon content of the EAS, particularly suited to address the multi-particle production in first interactions. The Collaboration examines the muon shower size using different datasets, in particular with inclined events (the electromagnetic component is largely absorbed before reaching the ground) [19] and with hybrid events (comparison of the measured ground signal to the expected one knowing the longitudinal profile) [20]. A muon deficit is observed in simulations compared to EAS data, from 30% to 80% at 10^{19} eV depending on interaction models.

7 Summary and perspectives

A wealth of valuable results is obtained by the Pierre Auger Observatory. The measured all-particle spectrum demonstrates the existence of a flux suppression above 40 EeV, whose origin is still not fully understood. A source effect seems to be favoured when considering the spectrum and the X_{max} evolution together. The image of a mixed composition around the ankle and a heavier composition at the highest energies is strengthened by different composition studies, and by anisotropy searches at small angular scales at the highest energies. The present photon limits also disfavour pure proton composition models. Top-down models were already disfavoured by results on UHE neutrino and photon fluxes, leading to an astrophysical source explanation, but no clear clue on any existing UHECR source has been revealed so far. The hint of dipolar structure in the arrival direction is a step forward in the understanding of the transitions between the galactic and extragalactic components. The comparison of measurements with model predictions remains a delicate operation, knowing that serious hints for deficiencies in UHE interaction models have been observed. The astrophysical scenario resulting from Auger measurements is very complex and cannot at present be understood in terms of a unique interpretation for the sources, propagation and composition of the UHECRs. The great value of these overall results will be reinforced by the knowledge of the nature of the UHECR primaries, event by event. This will be the key to answering the open questions on the highest energy and the suppression region. The Collaboration is undertaking a major upgrade program: AugerPrime (described elsewhere in these proceedings [21]), designed to improve the knowledge on mass composition, mainly by discriminating electromagnetic and muonic shower components from SD-based observables, by having a further and independent measurement. Such additional information will also be valuable to improving the understanding of hadronic interaction models. The upgraded Observatory will take data until 2024, with the objective of clarifying the UHECR puzzle.

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