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Study of the High Energy Cosmic Rays with the Pierre Auger Observatory

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Summary. — The Pierre Auger Southern Observatory, a hybrid detector for the study of ultrahigh energy cosmic rays (UHECRs), has now been operating for more than five years and has reached completion. This contribution describes the present status and performance of the Observatory, showing the advantages provided by the combined use of two different detection techniques. Selected results are presented with the emphasis given to the measurement of energy spectrum, arrival directions at the highest energies and search for photons as primary particles.

PACS 96.50.sb – Composition, energy spectra and interactions.
PACS 98.70.Sa – Cosmic rays (including sources, origin, acceleration, and interactions).
PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.

1. – Introduction

The origin of cosmic rays, and in particular at energies near 10^{20} eV, is a puzzling mystery. Cosmic rays with energies exceeding 10^{20} eV have been observed for more than 40 years (see, *e.g.* [1]) but due to their low flux only some ten events of such high energies could be detected up to recently. There are no generally accepted source candidates known to be able to produce particles of such extreme energies. Moreover, there should be a steeping in the energy spectrum near 10^{20} eV due to the interaction of cosmic rays with the microwave background radiation (CMB), due to the so-called GZK effect [2]. The non-observation of this effect in the data of the AGASA experiment [3] has motivated an enormous number of theoretical and phenomenological models trying to explain the absence of the GZK-effect and has stimulated the field as a whole.

Until very recently the experimental situation was very unclear, mainly because of a lack of statistics. At these extreme energies the flux of cosmic rays is very low, less than 1 particle per km^2 per century for cosmic rays above 10^{20} eV. Due to this, UHECRs can only be observed indirectly through the extensive air showers (EAS) they induce when colliding with a nucleus in the atmosphere, with the difficulty that the interpretation

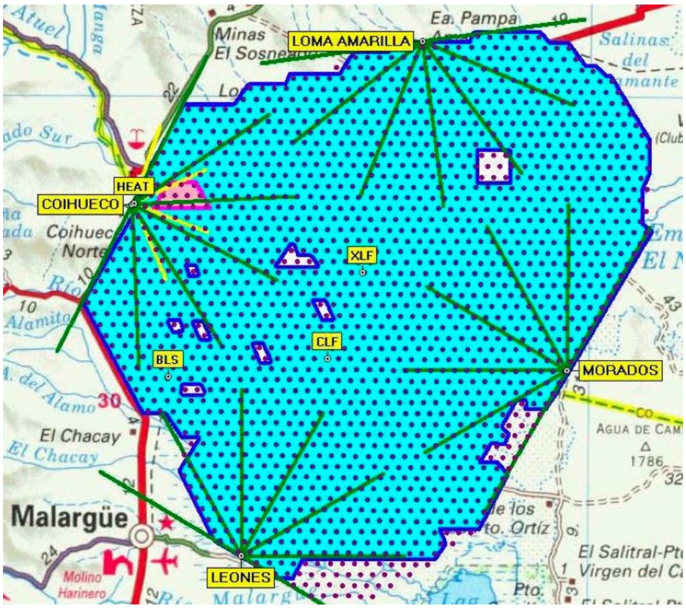

Fig. 1. – Actual deployment status of the array. Tanks within the shaded area are in operation.

of the observed EAS relies on models of hadronic interaction at energies that have not been still reached in man-made experiments. Some of the difficulties encountered in the interpretation of EAS are also believed to stem from the two different techniques with which cosmic rays were observed in past experiments, namely arrays of particle detectors spread over a large area in the case of (for instance) the AGASA experiment [3], and telescopes that collect the light produced by the fluorescence of the nitrogen molecules in the atmosphere excited by the passage of the charged particles in the shower in the case of the HiRes experiment [4].

The Pierre Auger observatory is dedicated to the high-statistics study of the high energy cosmic rays above $3 \cdot 10^{18}$ eV. It uses a hybrid design, coupling a surface array to fluorescence telescopes, the two techniques used by the two controversial experiments quoted above, which gathered most of the high energy events. It thus provides a powerful tool to probe the shape of the cosmic rays spectrum, to analyse directions and to try to measure composition. The southern site, near the town of Malargue in the Argentinian pampa, has already reached completion, and has been continuously taking data since 2004. After a description of the detector and a summary of its performance, a selection of the most recent results will be presented.

2. – Design and performance of the Pierre Auger Observatory

The Surface Detector (SD) of the Pierre Auger Observatory is composed of more than 1600 Water Cherenkov Detectors (WCD) extending over an area of 3000 km^2 with 1500 m spacing between detectors [5]. The construction was completed in June 2008. Figure 1 shows the current status of the array.

A water Cherenkov station consists of a cylindrical tank of 1.2 m average height and 10 m^2 area, containing 12 tons of purified water. Each station is an independent unit with low-power electronics, and a GPS and radio communication systems, all powered by a solar panel and two batteries. The Cherenkov light emitted by the particles entering a tank is reflected and diffused in its inner walls and collected by three 9-inches hemispherical photomultipliers. The corresponding signals are digitized by Flash Analog Digital Converters (FADC) in time slots of 25 ns, resulting in a FADC trace. The signal collected in a tank is calculated integrating in time the FADC trace, and is calibrated in units of Vertical Equivalent Muons (VEM) corresponding to the signal produced by vertical muons crossing the tank through its center. SD stations are calibrated on line every few minutes using atmospheric muons.

The SD is overlooked by four FD sites, each holding six fluorescence telescopes. All 24 fluorescence telescopes are in place and taking data. They detect the ultraviolet fluorescence light excited by the extensive air showers. Each telescope uses Schmidt optics to image a portion of the sky of $30 \times 30°$. The UV light is focused by spherical mirrors of $3\,\mathrm{m}^2$ of area on to a camera of 440 hexagonal photomultipliers each with a field of view of 1.5° diameter. They record the longitudinal shower development and thus provide a calorimetric measurement of the primary energy with little dependence on hadronic interaction models.

The Pierre Auger Observatory is the first large aperture instrument to routinely employ the so-called hybrid technique. About 13% of the operating time, the fluorescence light emitted by a shower and the timing and signal information from at least one SD is simultaneously recorded. This unique hybrid combination has enormous advantages which stem from the fact that one can simultaneously measure several shower observables with two different techniques.

3. – The energy spectrum of UHECRs

The hybrid nature of the Pierre Auger Observatory and the huge collecting area of the SD allows the energy spectrum of UHECRs to be measured with unprecedented accuracy and statistics. The hybrid events, which are air showers detected by both instruments, are very precisely measured and provide the energy calibration tool. The surface array, with its near 100% duty cycle, gives the large sample used here. Only "vertical" events, *i.e.* events with zenith angles 60° are used. For more inclined showers, due to different physical characteristics, a different analysis is applied [6].

The comparison of the shower energy, measured using fluorescence, with the SD energy estimator or a subset of high-quality hybrid events is used to calibrate the energy scale for the array. For so-called vertical events, the parameter chosen as SD energy estimator is called $S(1000)$, the signal at a distance of 1000 m from the core. The distribution of particles in the shower at the ground level is sampled at different distances from the core, and a fit to a Lateral Distribution Function (LDF) allows to determine $S(1000)$ [7]. $S(1000)$ has been shown to be rather insensitive to shower-to-shower fluctuations, nor does it require accurate knowledge of the shape of the LDF [8]. For a fixed cosmic ray (CR) energy, $S(1000)$ depends on the zenith angle of the event due to the attenuation of the shower particles in the atmosphere and other geometrical effects. Under the assumption of anisotropic flux of primary CRs, showers generated by primary particles of the same energy will arrive at the detector with the same frequency regardless of the zenith angle (assuming 100% efficiency). Hence, selecting showers arriving with a fixed intensity (energy) as a function of $S(1000)$, under different zenith angles, allows the measurement of the attenuation of $S(1000)$ with θ. This is the classical constant integral intensity cut method (CIC) [9]. This serves to convert $S(1000)$ at any given θ

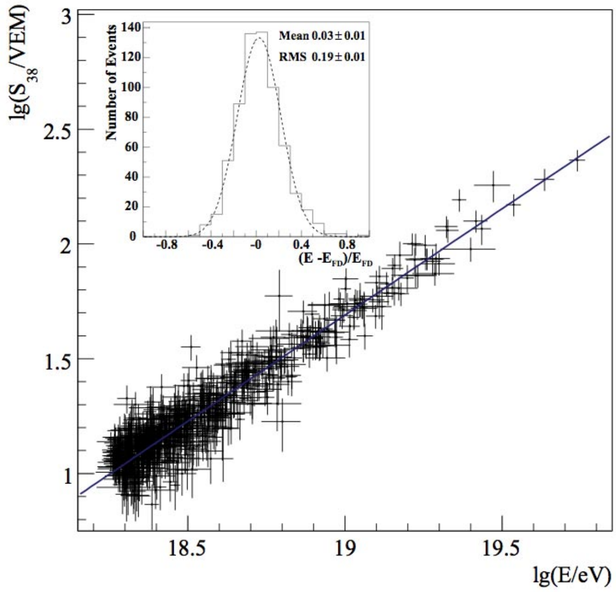

Fig. 2. – Correlation between $\log(S_{38})$ and $\log(E_{\mathrm{FD}})$ for the 661 hybrid events used in the fit. The full line is the best fit to the data. The fractional difference between the FD and SD energies is shown in the inset.

to $S(1000)$ at $\theta = 38$ (S_{38}) which is used as energy estimator. The angle of 38° minimises uncertainties, as this is the median zenith angle of the showers of interest. The calibration curve relating S_{38} and shower energy as obtained with FD data (E_{FD}) in hybrid events is shown in fig. 2, and it is used to find the energies of the bulk of the events in which there are only SD measurements.

The systematic uncertainty due to the calibration procedure is 7% at 10^{19} eV and 15% at 10^{20} eV. The systematic uncertainties on the energy scale E_{FD} sum up to 22% [10]. The largest uncertainties are given by the absolute fluorescence yield (14%) [11], the absolute calibration of the fluorescence telescopes (9%) and the uncertainty due to the reconstruction method of the longitudinal shower profile (10%). The uncertainty due to the water vapour quenching on the fluorescence yield (5%) is taken into account as described in [12]. Additionally, the wavelength-dependent response of the fluorescence telescopes (3%), the uncertainties on measurements of the molecular optical depth (1%), on the measurements of the aerosol optical depth (7%) and on multiple scattering models (1%) are included in the overall systematic uncertainty. The non-detected energy (due to the contributions of muons and neutrinos) correction contributes 4% to the total systematic uncertainty of 22% [13].

To build the spectrum, candidate showers are selected on the basis of the topology and time compatibility of the triggered detectors. The SD with the highest signal must be enclosed within an active hexagon, in which all six surrounding detectors were operational at the time of the event. Thus, it is guaranteed that the shower core is contained in the array. Applying this condition, the maximum statistical uncertainty in the reconstructed $S(1000)$ due to event sampling by the array is $\simeq 3\%$ [14]. The trigger efficiency is greater than 99% for energies above about $3 \cdot 10^{18}$ eV [15]. The exposure is calculated

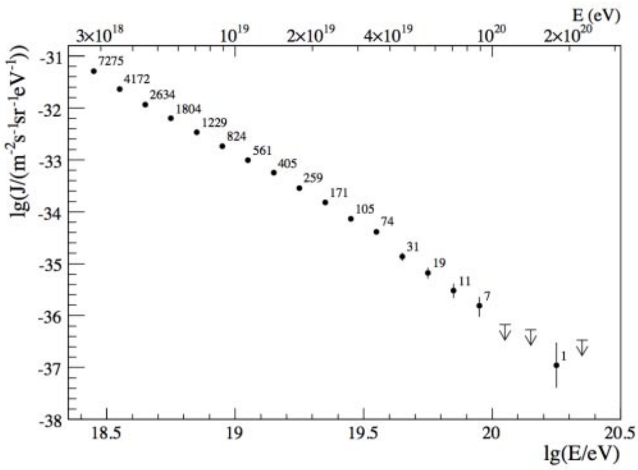

Fig. 3. – Energy spectrum derived from surface detector data calibrated with fluorescence measurements. Vertical error bars represent the statistical uncertainty only. The number of events in each bin is also given. A 22% systematic uncertainty in the absolute energy scale comes from the FD energy estimate.

by integrating the number of active detector stations of the surface array over time. Detailed monitoring information of the status of each surface detector station is stored every second and the exposure is determined with an uncertainty of 3%.

The surface detector is able to operate with an almost 100% duty cycle and collected the largest data set of ultra-high energy cosmic rays (UHECR) already during the construction phase. The spectrum corresponding to an exposure of $7000\,\mathrm{km}^2$ is shown in fig. 3, together with the event numbers of the underlying raw distribution [16].

The hypothesis that the cosmic ray spectrum continues with a constant slope above $4 \cdot 10^{19}$ eV is rejected with a significance greater than 6 standard deviations, consistently with the prediction by Greisen and by Zatsepin and Kuzmin.

4. – Arrival directions of UHECRs

Using data collected between 1 January, 2004 and 31 August, 2007, the Pierre Auger Observatory has reported evidence of anisotropy in the arrival directions of CR with energies exceeding $\simeq 60\,\mathrm{EeV}$ [17]. The arrival directions were correlated with the positions of nearby objects from the 12th edition of the catalog of quasars and active galactic nuclei (AGN) by Véron-Cetty and Véron (VCV catalog) [18]. This catalog is not an unbiased statistical sample, since it is neither homogeneous nor statistically complete. This is not an obstacle to demonstrating the existence of anisotropy if CR arrive preferentially close to the positions of nearby objects in this sample. The nature of the catalog, however, limits the ability of the correlation method to identify the actual sources of cosmic rays. The observed correlation identifies neither individual sources nor a specific class of astrophysical sites of origin. It provides clues to the extragalactic origin of the CR with the highest energies and suggests that the suppression of the flux is due to interaction with the cosmic background radiation.

The parameters of the test were chosen by an exploratory scan using events prior to 27 May 2006. The scan searched for a correlation of CR with objects in the VCV catalog with redshift less than $z_{\max}$ at an angular scale $\phi_{\max}$ and energy threshold E_{th}. The scan was implemented to find a minimum of the probability P that k or more out of a total N events from an isotropic flux are correlated by chance with the selected objects at the chosen angular scale. The minimum of P value was found for the parameters $z_{\max} = 0.018$, $\phi_{\max} = 3.1^{\circ}$, and $E_{\text{th}} = 56\,\text{EeV}$. The probability that an individual event from an isotropic flux arrives within the fraction of the sky prescribed by these parameters by chance is 0.21. The test was applied to data collected between 27 May 2006 and 31 August 2007. In this independent data, there were 13 events with energy above 56 EeV, of which 8 have arrival direction closer than 3.1° from the position of AGN less than 75 Mpc away, with 2.7 expected in average. The probability that this configuration would occur by chance is 1.7×10^{-3}. This correlation has a less than 1% probability to occur by chance if the arrival directions are isotropically distributed. Since the analysis reported in [17], the evidence for anisotropy has not strengthened [19].

Nevertheless, we have demonstrated the anisotropy of the arrival directions of the highest energy cosmic rays and their extragalactic origin. Our observations are consistent with the hypothesis that the rapid decrease of CR flux above 60 EeV, shown in sect. **1**, is due to the GZK effect. Additional data are needed to make further progress in the quest to identify the sites of ultrahigh energy CR origin.

5. – Limit on photon fraction in cosmic rays

Primary photons can experimentally be well separated from primary hadrons as they penetrate deeper into the atmosphere, particularly at energies above 10^{18} eV. Their shower development is also much less affected by uncertainties of hadronic interaction models due to the dominant electromagnetic shower component. At the highest energies the LPM effect further delays the shower development in the atmosphere (moreover increasing shower to shower fluctuations), whereas the pre-showering effect in the Earth magnetic field causes a more hadron like behavior (see [20] for a review on photon showers). Primary photons are of interest for several reasons: top-down models, originally proposed to explain the apparent absence of the GZK effect in AGASA data, predict a substantial photon flux at high energies [20]. In the presence of the GZK effect, UHE photons can also derive from the GZK process $p + \gamma_{\text{CMB}} \rightarrow p + \pi^0 \rightarrow p + \gamma\gamma$ and provide relevant information about the sources and propagation. Moreover, they can be used to obtain input to fundamental physics and EHE astronomy.

The SD collects large statistics and has some observables sensitive to composition. Monte Carlo predictions of these SD observables have been compared with those in nucleonic showers and have shown this sensitivity [21]. Based on these simulations, no photon candidates were identified in SD data implying that 2%, 5% and 31% of UHECRs are photons above 10^{19}, $2 \cdot 10^{19}$ and $4 \cdot 10^{19}$ eV, respectively.

Experimentally, photon showers can be identified with the FD by their longitudinal shower profile, most importantly by $X_{\max}$, the depth in the atmosphere at which the number of electrons in a shower reaches a maximum. $X_{\max}$ is measured with data from the FD of the Pierre Auger Observatory with an accuracy of less than $20\,\text{g}\,\text{cm}^{-2}$ if suitable cuts are made. Data on $X_{\max}$ can be used to discriminate between photonic and nucleonic UHE primaries. Due to the much lower multiplicity in particle production in an electromagnetic cascade, the $X_{\max}$ of a photon-induced EAS is typically greater than that of a nucleonic-induced shower.

In ref. [22] $X_{\max}$ was used to place an upper limit of 16% on the photon fraction above 10 EeV. The hybrid detector is fully efficient for shower above 1 EeV and it allows

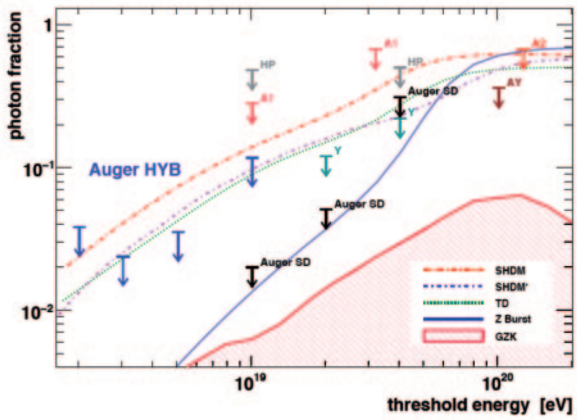

Fig. 4. – (Colour on-line) Upper limits on the photon fraction in the integral cosmic-ray flux for different experiments: AGASA (A1, A2) [24], AGASA-Yakutsk (AY) [25], Yakutsk (Y) [26], Haverah Park (HP) [27,28]. In black the limits from the Auger surface detector (Auger SD) [21] and in blue the limits above 2, 3, 5, and 10 EeV derived in this work (Auger HYB). The shaded region shows the expected GZK photon fraction as derived in [29]. Lines indicate predictions from top-down models, see [20].

thus composition study at lower energy than with the SD alone. Recently, the work was updated with more statistics and extended to data below 10 EeV. New upper limits of 3.8%, 2.4%, 3.5% and 11.7% on the fraction of photons above 2, 3, 5 and 10 EeV are obtained [23].

The derived upper limits are shown in fig. 4 along with previous experimental limits and model predictions (see ref. [20] for a review and references).

These limits improve significantly upon bounds from previous experiments and put strong constraints on certain models of the origin of cosmic rays. Current top-down models such as the super-heavy dark matter scenario do not appear to provide an adequate explanation of the UHE cosmic rays. In bottom-up models of acceleration of nuclear primaries in astrophysical sources, the expected photon fluxes are typically well below the current bounds [30].

6. – Conclusion

The Pierre Auger Observatory is the first large-scale UHECR detector to exploit the power of the hybrid technique, opening up a new era in experimental UHECR physics. The Observatory has been operating for more than 5 years and has now reached completion. Shower energies are determined in a way that minimises the dependence on models of hadronic interaction and composition. The energy spectrum of UHECRs above EeV energies was measured with vertical events. A steepening above $4 \cdot 10^{19}$ eV consistent with the GZK effect is apparent. Data from both FD and SD have been used to put stringent limits on the photon fraction in the UHECR flux. The sky has been shown to be anisotropic in UHECRs and their sources extragalactic.

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