The Pierre Auger Observatory – Recent Results and Plans

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The Pierre Auger Observatory, whose southern site has been completed recently, is the largest cosmic ray detector currently in operation. Data has been taken already during the construction phase since 2004 and an exposure equivalent to about one year of full operation of the southern observatory has been accumulated. The results obtained from the analysis of these data are reviewed and plans for the construction of the northern observatory are described.

1. Introduction

The Pierre Auger Observatory has been conceived to measure the flux, arrival direction distribution, and composition of ultra-high energy cosmic rays (UHECRs) with full sky coverage. The southern site of the Auger Observatory, located near Malargüe (Argentina) has been completed in June 2008 and preparations for the construction of the northern site in eastern Colorado, USA, are in progress. In addition there are several enhancement detectors being built to extend the energy range of the southern observatory to lower energy and to test new shower measurement techniques. One of the key features of the Auger Observatory is the capability to measure showers with both ground-based particle detectors and fluorescence light telescopes. This hybrid detection technique allows us to combine the calorimetric measurement of the shower energy through fluorescence light with the high-statistics data of a surface array.

After giving a short description of the southern observatory we will discuss the main physics results obtained so far. Results on hadronic interactions and elemental composition, being of particular interested to this symposium, are found in separate contributions \cite{1,2}. In the second part of this article enhancements of the southern Auger observatory that are currently under construction are discussed and the plans for the northern observatory are summarized.

2. The southern observatory

The southern observatory, located at an altitude of about 1400 m a.s.l. in the Province of Mendoza comprises 1600 water-Cherenkov detectors and 24 fluorescence telescopes. The water-Cherenkov detectors are deployed on a triangular grid of 1500 m spacing, covering an area of more than 3000 m\textsuperscript{2}, and form the surface detector (SD). The fluorescence telescopes, referred to as fluorescence detector (FD) in the following, can be operated only in clear, moonless nights. The duty cycle of the FD is about 13\%, while nearly 100\% is achieved with the SD. A detailed description of an engineering array, which was built for preparing the construction of the full array, can be found in \cite{3}. The status and detector performance is discussed in \cite{4}.

The layout of the southern Auger site is shown in Fig. 1. The gray area indicates stations that are integrated in data taking. Some parts of the territory have been inaccessible during the construction due to the high water levels of the previous years. The 24 fluorescence telescopes of the FD are located in four buildings on small hills (Los Leones, Coihueco, Los Morados and Loma Amarilla) at the periphery of the SD array. In addition there are weather stations, two laser facilities, and a balloon launching facility for ensuring continuous monitoring of the atmospheric conditions and performing telescope calibration.
2.1. Surface detector

The SD stations are powered by solar panels and batteries and communicate through a microwave link with the central data acquisition system. Each of the water-Cherenkov detectors contains 12 tonnes of purified water, which is viewed by three 9” photomultipliers. The signal is sampled at 40 MHz and absolute time is obtained from GPS receivers. A relative time synchronization of the stations of about 16 ns is achieved.

The SD is sensitive to both charged particles and photons since the latter convert in the water. The signal of an SD station is quantified in terms of the response of an SD station to a muon traveling vertically and centrally through it (a vertical equivalent muon or VEM). Calibration of each station is carried out continuously with atmospheric muons, reaching an accuracy of about 2%. For a typical shower of $10^{19}$ eV half of the signal at 1000 m from the core is due to muons.

There are two types of trigger conditions applied to select air shower events. The threshold trigger condition is satisfied for a station if a signal of at least 3.2 VEM is recorded. The time-over-threshold trigger requires a signal greater than 0.2 VEM for 12 consecutive time bins of 25 ns in a sliding window of 3 μs. An event is accepted as candidate event if three stations send a trigger within a given time window. The signal of the surrounding stations is read out and used for event reconstruction independent of their trigger status. The trigger efficiency reaches 100% for showers with an energy $E > 10^{18.5}$ eV and zenith angles smaller than 60° [5].

The arrival direction of an event is determined from the signal start times assuming a curved shower front as expected from simulations. An angular accuracy of about 1° is obtained for showers with $E > 10^{19}$ eV. The lateral distribution of the SD signal is fitted in each event to find the VEM size at 1000 m, $S(1000)$ [6]. The uncertainty in $S(1000)$ is about 10%, accounting for statistical fluctuations of the signals, systematic uncertainties in the assumption of the fall-off of signal with distance, and the shower-to-shower fluctuations.

2.2. Fluorescence detector

The fluorescence telescopes employ Schmidt optics and cover each a field of view of 30° in azimuth and 1.5° – 30° in elevation. The diaphragm of the telescopes is equipped with a UV band pass filter (50 nm FWHM centered at 353 nm). Light is focused on a camera containing 440 hexagonal PMTs at the focal surface of a segmented, spherical mirror of 11 m² effective area. A lens in the shape of a corrector ring is used to improve the point spread function of the telescopes. The signal of the PMTs is sampled at 100 MHz. The telescopes are calibrated by an end-to-end technique using a drum for uniformly lighting the telescope diaphragm and a NIST calibrated light source [7].

The event trigger of the telescopes is based on a pattern recognition algorithm that selects events with four triggered PMTs out of a line-like pattern of 5 PMTs for a time window of 1 μs. In a second step the timing information is used and a first estimate of the shower geometry is derived.
If the shower candidate passes the on-line quality selection criteria a signal is sent to the central DAQ system and the SD stations of the sectors of relevance are read out. This cross trigger allows us to record also events which would not trigger the surface array due to their low energy.

Although showers can be reconstructed completely just using the data of the fluorescence telescopes, we always use the information from at least one station of the SD. This additional information improves considerably the reconstruction accuracy [8]. The shower track on the camera defined a shower-detector plane. The angle of the shower axis within this plane is derived from timing information of the camera PMTs and the corresponding SD station with the largest signal. The hybrid-reconstructed events have an angular accuracy that improves from 0.8° at $3 \times 10^{18}$ eV to 0.5° above $10^{19}$ eV. The longitudinal shower profile is fitted with a Gaisser-Hillas function [9], accounting for different Cherenkov light contributions and atmospheric effects [10].

3. Energy spectrum

The flux measurement at ultra-high energy reported here is based on data of the period from 1 January 2004 to 31 August 2007, corresponding to a total exposure of $(7000 \pm 200)$ km$^2$ sr yr [11]. The derivation of the energy spectrum proceeds in two steps. First the constant intensity cut (CIC) method [12] is used to assign to all showers with zenith angles $\theta < 60^\circ$ an equivalent $S(1000)$ value, called $S_{38^\circ}$. In the second step, the relation of $S_{38^\circ}$ to the shower energy is found by investigating events that have triggered both the SD and the FD.

The slant depth of the surface array varies from 870 g/cm$^2$ for vertical showers to 1740 g/cm$^2$ for showers at zenith angle $\theta = 60^\circ$. The signal $S(1000)$ is attenuated at large slant depths. Its dependence on zenith angle is derived empirically by exploiting the nearly isotropic intensity of cosmic rays. By fixing a specific intensity $I_0$ (event counts per unit of sin$^2 \theta$), one finds for each zenith angle the value of $S(1000)$ such that $I(> S(1000)) = I_0$. Given $S(1000)$ and $\theta$ for a measured shower, the energy parameter $S_{38^\circ}$ is defined by $S_{38^\circ} = S(1000)/CIC(\theta)$ with $CIC(\theta) = 1 + a \cdot x + b \cdot x^2$ and $x = \cos^2 \theta - \cos^2 38^\circ$. The parameters are $a = 0.94 \pm 0.06$ and $b = -1.21 \pm 0.27$ [13].

![Figure 2. Correlation between lg $S_{38^\circ}$ and lg $E_{FD}$ for the 661 hybrid events used in the fit. The full line is the best fit to the data. The fractional differences between the two energy estimators in the inset.](image)

The correlation of $S_{38^\circ}$ with the shower energy $E_{FD}$ derived from the longitudinal shower profile is shown in Fig. 2, together with the least-squares fit of the data to a power-law, $E_{FD} = a \cdot S_{38^\circ}^{b}$. The best fit yields $a = (1.49 \pm 0.06 \text{(stat)} \pm 0.12 \text{(syst)}) \times 10^{17}$ eV and $b = 1.08 \pm 0.01 \text{(stat)} \pm 0.04 \text{(syst)}$ with a reduced $\chi^2$ of 1.1. $S_{38^\circ}$ grows approximately linearly with energy. The energy resolution, estimated from the fractional difference between $E_{FD}$ and the derived SD energy, $E = a \cdot S_{38^\circ}^{b}$, is shown as inset. The root-mean-square deviation of the distribution is 19%, in good agreement with the quadratic sum of the $S_{38^\circ}$ and $E_{FD}$ statistical uncertainties of 18%. The calibration accuracy at the highest energies is currently still
limited by the number of events: the most energetic is $\sim 6 \times 10^{19} \text{eV}$. The possibility of a change in hadronic interactions or in the mean primary mass above this energy will be investigated once more data are available.

The obtained energy spectrum is shown in Fig. 3 [11]. Systematic uncertainties on the energy scale due to the calibration procedure are 7% at $10^{19} \text{eV}$ and 15% at $10^{20} \text{eV}$, while a 22% systematic uncertainty in the absolute energy scale comes from the FD energy measurement.

To examine the spectral shape at the highest energies, we fit a power-law function between $4 \times 10^{18} \text{eV}$ and $4 \times 10^{19} \text{eV}$, $J \propto E^{-\gamma}$. The spectral index obtained is $2.69 \pm 0.02\text{(stat)} \pm 0.06\text{(syst)}$, with the systematic uncertainty coming from the calibration curve. A single power-law hypothesis for all energies above $4 \times 10^{18} \text{eV}$ is rejected with a significance of more than 6 standard deviations [16], a conclusion independent of the systematic uncertainties currently associated with the energy scale. The flux suppression is similar to what is expected from the GZK effect [17,18] for protons or heavy nuclei [19], but could also be related to a change of the shape of the mean injection spectrum of the sources.

In Fig. 3 the fractional differences with respect to an assumed flux $\propto E^{-2.69}$ are shown. HiRes I data [15] show a softer spectrum where our index is 2.69 while the energy of suppression, defined as the position where the flux falls to 50% of the power-law extrapolation, agrees within the quoted systematic uncertainties.

Analyzing hybrid events with a good shower profile being detected in the FD and at least one SD station triggered, the spectrum presented here has been extended down to $10^{18} \text{eV}$. The ankle of the cosmic ray flux at about $E = 10^{18.6} \text{eV}$ is clearly seen in this hybrid spectrum [20], which will not be discussed here.

4. Arrival direction distribution

An anisotropy in the arrival direction distribution of cosmic rays in the energy range of the GZK suppression is expected because of the highly anisotropic matter distribution on distance scales of 100 Mpc, provided the galactic and extragalactic magnetic fields are not too strong relative to the charge of the particles and the source distribution follows that of matter. Indeed, analyzing a data set with an integrated aperture of $9,000 \text{km}^2 \text{sr} \text{year}$, a correlation between the arrival directions of the cosmic rays with $E > 5.7 \times 10^{19} \text{eV}$ measured by the Pierre Auger Observatory and the positions of nearby AGN from the 12th edition of the catalog of quasars and active galactic nuclei by Véron-Cetty and Véron (V-C catalog) [21] has been found [22,23].

To quantify a possible correlation the probability $P$ for a set of $N$ events from an isotropic flux to contain $k$ or more events at a maximum angular distance $\psi$ from any member of a collection of candidate point sources is used. $P$ is given by the cumulative binomial distribution $\sum_{j=k}^{N} C_j^N p^j (1 - p)^{N-j}$, where the parameter $p$ is the fraction of the sky (weighted by the exposure) defined by the regions at angular sepa-
Figure 4. Hammer-Aitoff projection of the arrival directions of cosmic rays with $E > 5.7 \times 10^{19}$ eV (circles) and directions of AGNs (stars) as given in the Veron-Cetty & Veron catalog [21] (equatorial coordinates). The directions of the three strongest radio sources are also shown.

ration less than $\psi$ from the selected sources. Using data acquired between 1 January 2004 and 26 May 2006, we scanned for the minimum of $P$ in the three-dimensional parameter space defined by maximum angular separation $\psi$, maximum redshift $z_{\text{max}}$, and energy threshold $E_{\text{th}}$. A minimum of $P$ for the parameters $\psi = 3.1^\circ$, $z_{\text{max}} = 0.018$ ($D_{\text{max}} = 75$ Mpc), and $E_{\text{th}} = 5.6 \times 10^{19}$ EeV was found: 12 events among 15 correlate with the selected AGN, whereas only 3.2 were expected by chance if the flux were isotropic.

To validate this result a prescription was set up and applied to the following, independent data set collected between 27 May 2006 and 31 August 2007 [22,23]. In this data set, 13 events with $E > 5.6 \times 10^{19}$ eV were found, of which 8 have arrival directions closer than $3.1^\circ$ from the positions of AGN less than 75 Mpc away, with 2.7 expected on average. The probability that this configuration would occur by chance if the flux were isotropic is $1.7 \times 10^{-3}$. Following our search protocol and based on the independent data set alone, we reject the hypothesis of isotropy in the distribution of the arrival directions of cosmic rays with the highest energies with at least a 99% confidence level.

Having accepted the hypothesis of correlation, a re-scan the full data set from 1 January 2004 to 31 August 2007 is done. The minimum probability for the hypothesis of isotropic arrival directions is found for the parameter set $z_{\text{max}} = 0.017$ ($D_{\text{max}} \approx 71$ Mpc), $\psi = 3.2^\circ$, and $E_{\text{th}} = 5.7$ EeV [23]. The arrival directions of the 27 events and AGN directions from the V-C catalog selected with these cuts are shown in Fig. 4. The anisotropy is clearly visible. We note the proximity of several events close to the supergalactic plane, and also that two events arrive within $3^\circ$ of Centaurus A. Of course, the V-C catalog does not contain all existing AGN and is not an unbiased statistical sample of them. This, however, is not an obstacle to demonstrating the existence of anisotropies but may affect our ability to identify the cosmic-ray sources unambiguously.

No anisotropy of the arrival direction distribution or correlation with the galactic center or BL Lacs is found at lower energy [24–27].

5. Hadronic composition

The mean depth of shower maximum, $\langle X_{\text{max}} \rangle$, has been derived from hybrid events collected between 1 December 2004 and 30 April 2007 [28]. A good resolution of the reconstructed $X_{\text{max}}$ is achieved by requiring the reconstructed $X_{\text{max}}$ to
be within the observed part of the shower profile and the reduced $\chi^2$ of a fit with a Gaisser-Hillas function should not exceed 2.5. A set of fiducial volume cuts is applied to allow for an unbiased measurement of the $X_{\text{max}}$-distribution: Energy dependent cuts on the zenith angle and the maximum SD station-core distance ensure a single-station trigger probability near one for protons and iron at all energies. Furthermore, to minimize systematic uncertainties from the relative timing between the fluorescence and surface detectors, the minimum viewing angle under which a shower was observed is required to be larger than 20°. This cut also removes events with a large fraction of direct Cherenkov light.

The total syst. uncertainty of the derived $X_{\text{max}}$ is $\leq 15\, \text{g/cm}^2$ at low energies and $\leq 11\, \text{g/cm}^2$ above $10^{18}\, \text{eV}$. The dominating contribution is the long-term validity of the monthly average molecular profiles used in this analysis, which is estimated to be $\leq 6\, \text{g/cm}^2$.

In Fig. 5 the mean $X_{\text{max}}$ is shown as a function of energy together with predictions from air shower simulations [29–32]. The data indicate clearly a mixed composition at all energies. A detailed interpretation of the data is, however, ambiguous due to the uncertainties of modeling hadronic interactions at highest energies. Within the syst. and stat. uncertainties, the Auger data agree with the results from the HiRes stereo [33] and HiRes-MIA [34] measurements.

A simple linear fit of the data,

$$\langle X_{\text{max}} \rangle = D_{10} \cdot \lg (E/\text{eV}) + c,$$

yields an elongation rate of $54 \pm 2$ (stat.) $\text{g/cm}^2$/decade, but does not describe our data very well ($\chi^2/\text{Ndf} = 24/13, P < 3\%$). Allowing for a break in the elongation rate at an energy $E_b$ gives a satisfactory fit with $\chi^2/\text{Ndf} = 9/11, P = 63\%$ and $D_{10} = 71 \pm 5$ (stat.) $\text{g/cm}^2$/decade below $E_b = 10^{18.35}\, \text{eV}$ and $D_{10} = 40 \pm 4$ (stat.) $\text{g/cm}^2$/decade above this energy. This fit is indicated as a gray line in Fig. 5.

6. Search for photons and neutrinos

Detecting a large fraction of ultra-high energy photons in the cosmic ray flux would be a clear signature for top-down source scenarios [35]. In addition such photons are produced in the interaction of UHECRs during acceleration or propagation. Photon showers penetrate $200 - 300\, \text{g/cm}^2$ deeper into the atmosphere than hadron-induced showers. This fact is used in the Auger photon limit based on the analysis of the 29 highest energy showers observed in hybrid mode until February 2006 [37]. Regarding SD data, the signal risetime at ground and the curvature of the shower front are also closely related to the depth of shower maximum. Using these observables, the higher duty cycle of the SD allowed us to improve the FD-based photon limit in [36]. The maximum fraction of photons is 2.0% above $10^{19}\, \text{eV}$ and 62% above $8 \times 10^{19}\, \text{eV}$, which corresponds to limits on the flux of photons of $6.9 \times 10^{-3}$ and $1.7 \times 10^{-3}\, \text{km}^{-2}\, \text{sr}^{-1}\, \text{yr}^{-1}$, respectively, with a confidence level of 95%. Many top-down source models for UHECRs are disfavored or even excluded by these measurements. A compilation of current limits is shown together with model predictions in Fig. 6.
Figure 6. Compilation of integral limits on the fraction of photons in the UHECR flux – Auger SD analysis (black arrows); HP: Haverah Park; A1, A2: AGASA; AY: AGASA-Yakutsk; Y: Yakutsk; FD: Auger hybrid limit. The data are compared with a selection of model predictions. For references to the data and models, see [36].

The large cross section of the surface detector stations allow the detection of very inclined and even horizontal air showers. With the slant depth exceeding 30,000 g/cm² for nearly horizontal showers, only neutrino-induced showers are expected to give a shower signal with a significant electromagnetic component. The largest sensitivity is reached for Earth-skimming tau neutrinos, whose signature would be slightly upward going showers if they produce taus in charged current interactions that decay above the SD [38,39].

The data collected between 1 January 2004 and 31 August 2007 has been analyzed and an upper limit on the diffuse flux of $\nu_\tau$ at EeV energies derived [40]. Assuming an $E_\nu^{-2}$ differential energy spectrum the limit set at 90% C.L. is $E_\nu^2 \frac{dN_{\nu_\tau}}{dE_\nu} < 1.3 \times 10^{-7}$ GeV cm$^{-2}$ s$^{-1}$ sr$^{-1}$ in the energy range $2 \times 10^{17}$ eV $< E_\nu < 2 \times 10^{19}$ eV. A compilation of recent limits on the single-flavour neutrino flux at very high energy is shown in Fig. 7.

Figure 7. Compilation of limits at 90% C.L. for a diffuse flux of $\nu_\tau$. Limits from other experiments are converted to a single flavor assuming a 1 : 1 : 1 ratio of the 3 neutrino flavors and scaled to 90% C.L. where needed. For references, see [40]. Two different formats are used: differential (squares) and integrated (constant lines). The shaded curve shows the range of expected fluxes of GZK neutrinos from Ref. [41,42], although predictions almost 1 order of magnitude lower and higher exist.

7. Enhancements of the southern observatory

After having completed the southern observatory, there are several enhancements under construction to improve the sensitivity of the observatory at low energy. Many of these activities are motivated by the interest in understanding the transition between galactic and extragalactic cosmic rays [43].

Three High Elevation Auger Telescopes (HEAT) are being built near the Coihueco fluorescence station. These telescopes will cover an elevation angle from about 30 – 60° and improve the sensitivity to and reconstruction of the longitudinal shower profile at low energy [44]. It is expected that shower with energies as low as $10^{17.2}$ eV will be well reconstructed.

In front of HEAT, a graded infill array is foreseen to lower the trigger threshold and to allow direct muon detection. The Auger Muons and Infill for the Ground Array (AMIGA) will consist of SD stations and buried muon detectors of 30 m² effective area [45]. AMIGA will have nearly full
acceptance for showers of $10^{17}$ eV. The layout of AMIGA and HEAT is shown in Fig. 8.

It is also planned to deploy a radio antenna array to study the feasibility of using this new detection technique for air shower measurements [46]. First measurements with different antennas have been carried out in preparation of the development of a design for such an array.

8. Towards a northern observatory

The measurements with the southern observatory have confirmed the existence of a flux suppression at the highest energies. This flux suppression, together with the observed anisotropy does not only open a door to identifying the sources of UHECRs directly, but offers also unique means for studying the physics of UHECRs. For example, depending on the source scenario, it is expected that the highest energy cosmic rays with $E > 7 \times 10^{20}$ eV are either mainly protons or iron nuclei, or a superposition of the two. The intermediate elements are photo-disintegrated much more effectively than iron and are thus suppressed for sources at large distances [47]. Knowing the composition and collecting events with high statistics will allow us to identify nearby sources or source regions, measure magnetic fields, perform particle physics studies and much more.

![Figure 8. Layout of the planned enhancements AMIGA and HEAT for the southern observatory.](image1)

![Figure 9. Layout of the northern observatory planned in south-eastern Colorado. Each dot is the position of one SD station. The distance range covered by fluorescence telescopes is indicated by (semi-)circles. Laser stations for calibration and atmospheric monitoring are denoted by DLF (distant laser facility) and NAILS (nitrogen automated independent laser system).](image2)

The aim of the northern observatory is the measurement of UHECRs with high statistics in the energy range of the GZK suppression. It will also provide full sky coverage in combination with the southern observatory.
The site of the northern observatory is located in south-eastern Colorado, USA, near the town Lamar. The average altitude is with 1300 m very similar to that of the southern site. The latitude of 38° N ensures full sky coverage and a rather flat total exposure of the Auger Observatory [48].

The northern observatory has been optimized for measuring UHECRs above $10^{19.5}$ eV. An array of 4000 SD stations will cover an area of about 20,000 km². Making use of the existing county roads every mile, the stations will be deployed on a $\sqrt{2}$-mile grid (2.3 km), placing a station on every other road intersection. This array will reach full acceptance only at $10^{19.5}$ eV. A infill array of 400 stations will allow the measurement of showers with an energy threshold similar to that of the southern site. The FD will consist of 39 fluorescence telescopes in 5 stations. With an anticipated maximum viewable distance of 40 km, almost full coverage of the SD array is achieved.

9. Conclusions

The Pierre Auger Observatory is collecting data since January 2004. The analysis of data equivalent to about one year of operation of the full southern observatory has confirmed the suppression of the cosmic ray flux at ultra-high energy. In accordance with the expectation of this flux suppression being related to the GZK effect, the arrival direction distribution of cosmic rays in the energy range of suppression is found to be anisotropic. There is, however, still the possibility that the flux suppression is due in part to a change of the mean injection spectrum of the sources. Previous claims of anisotropies at lower energy could not be confirmed. The fraction of gamma-rays in the cosmic ray flux is found to be small, disfavoring many exotic source scenarios. The data on shower profiles indicate a mixed elemental composition if interpreted with currently available hadronic interaction models. Based on the data and results from the southern observatory, a design of the northern observatory has been developed.

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