The Pierre Auger Observatory
— Status and first results —

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Abstract. The Pierre Auger Observatory, is optimised to study cosmic rays at energies above $10^{18.3}$ eV. To achieve a uniform, full sky coverage, the baseline design of the Observatory comprehends two sites, one in the southern hemisphere, another one in the northern hemisphere. The southern observatory, currently under construction in Malargüe, Argentina, has started data taking with what amounts to about 1/4 of the full installation. We present the current status of the installation and first results from the dataset, collected from January 2004 to June 2005.

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INTRODUCTION

The observation of cosmic rays extends to energies above $10^{20}$ eV or 16J. It is still a mystery by which mechanism nature manages to accelerate subatomic particles to macroscopic energies. The exact nature of these ultra-high energy cosmic rays (UHECR) is also unknown. We don’t know if they are protons or heavier atomic nuclei, nor are we sure if there are photons in the primary cosmic ray beam.

To cast light on the mystery of the UHECRs, the Pierre Auger Collaboration decided to build the world’s largest cosmic ray observatory [1]. The observatory is split into two sites, one in the northern hemisphere and one in the southern hemisphere. The southern site is currently under construction, near Malargüe, in Mendoza, Argentina. The northern site will be located near Lamar, in Colorado, USA.

UHECRs are detected indirectly, by the observation of the extended air shower (EAS) which they create in the atmosphere. There are two established techniques for the detection of EAS: the sampling of the shower front using an array of detectors on the ground and the detection of the fluorescence of atmospheric nitrogen, induced by the charged particles of the air shower. The Pierre Auger Observatory combines the two techniques in its unique hybrid design. The southern site will cover an area of roughly $3000\text{km}^2$ with 1600 surfaced detector stations. A set of 24 fluorescence telescopes is installed in 4 buildings, located along the border of the surface array.

The hybrid design of the Pierre Auger Observatory makes it possible to measure a larger set of observables of EAS, since the surface array measures the lateral distribution of the shower, whereas the fluorescence detector observes the longitudinal development of the shower. A hybrid design also permits to overcome the weaknesses of either of the techniques alone. For example, for the measurement of the spectrum of UHECRs,
one combines the superior energy determination of the fluorescence technique with the larger statistics and geometrical aperture of the surface array.

**A QUICK REVIEW OF THE PHYSICS OF UHECRS**

Our knowledge of the highest energy cosmic rays is still very limited, even 40 years after the detection of the first cosmic ray with an energy above $10^{20}$ eV, see for example [2, 3] and references therein. Different models for the acceleration of UHECRs and for the distribution of their sources predict different observables. The best know prediction, made independently by K. Greisen [4] and by G.T. Zatsepin and V.A. Kuz'min [5], is probably the so-called GZK cut-off. They observed that protons above $\approx 5 \times 10^{19}$ eV loose most of their energy over distances of 50 to 100 Mpc due to interactions with the cosmic microwave background. Other cosmic ray primaries suffer similar losses and, as a consequence, one expects a rapid fall-off of the cosmic ray spectrum above the GZK energy. Observational indications that the spectrum of UHECR might extend beyond the GZK cut-off motivated the development of a large number of models that avoid one or several of the assumptions behind the prediction of the GZK cut-off. One class, the top-down models, predicts a sizable fraction of photons at the highest energies. Different models, combined with assumptions about the type of the primary cosmic ray and about galactic and inter-galactic magnetic fields, predict point sources or anisotropy patterns for the arrival of UHECR.

The two predecessor experiments to the Pierre Auger Observatory, AGASA [6] and HiRes [7], measured the UHECR spectrum, with contradicting conclusions. HiRes reports the observation of the GZK cut-off [8, 9], whereas AGASA does not see this fall-off [10, 11]. The AGASA experiment uses a surface array to measure cosmic rays, whereas the HiRes experiment is an air fluorescence detector. The Pierre Auger Observatory, with its increased statistics and with its possibility to compare the two techniques, will resolve this puzzle and more of the open questions around the highest energy cosmic rays.

**STATUS AND PERFORMANCE OF THE OBSERVATORY**

The construction of the southern site of the Pierre Auger Observatory is still on-going. In the following, we present the current status of the installation an the performance of the instrument.

**The surface detector**

The surface array of the Pierre Auger Observatory consists of a triangular grid of surface stations with a spacing of 1.5 km. Each station consists of a rotomolded tank of 10 m$^2$ area, filled with 12 m$^3$ of purified water. The detection of the particles of the front of the air shower is via the Cherenkov light they emit in the water. This light is captured by three 9” photo-multiplier tubes (PMTs). The signal is taken both from the
anode and from the last dynode. All signals are sampled continuously by 10 bit, 40 MHz FADCs. The relative amplification of the anode and dynode channels is chosen to create a dynamic range which allows for the detection of signals from a few photo electrons up to $10^5$ photo electrons. A front-end board with a PLD-based 1st level trigger, connected to the local station controller, reads the data. The station controller implements a second level trigger. It also handles the communication with the central data acquisition system. The clock of all the local stations are synchronised using the signals from the global positioning system (GPS). The time resolution achieved with this system is better than 20ns. The local station is powered from a battery which is recharged by a solar panel, mounted on top of the tank. More details of the surface detector can be found in [1, 12].

A consequence of the conditions, under which the detector operates in the field, is continuous monitoring is of utmost importance in order to guarantee the quality of the data. Temperatures, battery status and trigger rates as well as general weather data like pressure, humidity, and wind speed, are continuously recorded.

At the time of writing, nearly 1160 stations are in the field, of which about 970 are operational and taking data.
The fluorescence detector

The fluorescence detection system consists of 24 telescopes, installed in 4 sites along the perimeter of the surface array, overlooking the sky above the array. Three of the four sites are fully equipped and operational. The fourth building is currently under construction.

Each telescope has a field of view of $30 \times 30^\circ$. It consists of a Schmidt camera with a corrector ring to enlarge the aperture. A $3.5 \times 3.5 \text{m}^2$ spherical mirror reflects the image onto the camera, mounted in the focal plane. The camera consists of 440 PMTs, each with a field of view of $1.5^\circ$ diameter. The corrector ring allows to enlarge the aperture of the camera from 1.7 m diameter to 2.2 m, increasing the effective light collecting area by a factor two. A filter, matched to the nitrogen fluorescence spectrum (approximately 300 nm to 400 nm), reduces the background light from the sky and doubles as a window, protecting the delicate optics from the exterior.

The telescopes are calibrated carefully, using an absolute and a relative procedure [13,14]. The absolute calibration is performed three to four times a year, using a mobile light source in a drum diffuser, which is mounted on the outside of the aperture of a telescope [13]. For the relative calibration, optical fibres illuminate the camera and mirrors in three different positions [14]. Tracking the relative calibration information for each pixel fixes the gain information of each of them.

The calibration of the fluorescence detector is verified by detecting and reconstructing vertical and inclined laser shots from the central laser facility (CLF) [15]. By firing a laser beam with a well measured energy and geometry, one can verify the accuracy of the geometrical reconstruction, of the energy determination, and measure the atmospheric scattering and absorption.

During the reconstruction of an event detected by the fluorescence detector, one has to estimate the number of photons emitted by the shower from the number of photons observed. To be able to do this, one has to know the atmospheric conditions. The collaboration operates a sophisticated atmospheric monitoring system for this purpose.
Details can be found in [16, 17].

Hybrid detection

In a hybrid event, an air shower is detected simultaneously but the fluorescence and surface detectors of the observatory. Only about 10% of all events are hybrid, reflecting the duty cycle of the fluorescence detector, which can operate only on clear, moonless nights.

Fluorescence events detected from a single FD site are difficult to reconstruct. The plane containing the shower and the detector site can be determined straightforwardly and with good precision. The determination of the shower inside that plane in difficult though. One needs additional information, either from a second FD site, or from the surface array. It turns out that the precision of the reconstruction is similar for either of the two techniques. The first technique, stereo detection, is used by the HiRes collaboration. The Pierre Auger Collaboration decided to use the second technique, the hybrid detection, as the main technique. For higher energy events, the Pierre Auger Observatory is also capable of performing stereo or higher order observation of EAS.

To maximise the number of hybrid events, a cross-triggering mechanism is built into the data acquisition of the observatory. This is necessary, since the trigger threshold of the FD is lower for nearby showers than that of the SD. To overcome this problem, the fluorescence detector notifies the surface detector of any event trigger it generates. Thereby, a trigger can be generated for a sub-threshold SD event.
During the geometrical reconstruction of a hybrid event, one fits simultaneously timing information from the FD pixels and SD timing. The resulting accuracy is 50 m for the core position and 0.6° for the arrival direction [18]. This resolution is verified analysing reconstructed laser shots from the CLF (figs. 3 and 4).

For more details about the hybrid detection technique and performance, see [1, 19] and references therein.

**FIRST RESULTS**

The data taken during the 18 month period from January 2004 to June 2005 has been analysed by the collaboration. The integrated aperture over that period is 1750 km$^2$sr yr. This aperture is similar to the integrated aperture over the lifetime of the AGASA experiment (1619 km$^2$sr yr) and to that of the HiRes experiment (5000 km$^2$sr yr). The statistics of the data set is therefore similar.

**Photon limit**

Some theoretical models predict the presence of a significant amount of photons in the primary cosmic radiation at the highest energies. A limit on the number of photons can therefore be used to eliminate some of those models.

The analysed data set of the Pierre Auger Observatory has been used to derive a limit on the photon fraction at energies above 10$^{19}$ eV [20, 21]. A set of cuts has been applied to this set, requiring a good hybrid geometry and fit, an energy $E > 10^{19}$ eV, at least 6 triggered PMTs, a well-fitted shower profile (see, e.g., fig. 5), and a visible $X_{\text{max}}$. Using a fluorescence based energy estimate leads to conservative estimates of the number of events accepted, since electromagnetic showers, as induced by photons, have
less invisible energy. One is therefore more likely to loose nuclei rather than photons. After all cuts, a set of 29 events remains. Analysing each of these events, comparing them with events simulated under equivalent conditions, one notes that all the events develop higher in the atmosphere than a typical photon event (e.g., fig. 6). After a careful analysis [20], we conclude that the upper limit of the photon fraction is 16% at 95% confidence level.

**UHECR spectrum**

A first spectrum for UHECRs above 3 EeV has been determined using the first data set analysed. At this energy, the surface detector is fully efficient and the aperture is given by the geometry of the surface array [22, 23].

The energy converter used to assign an energy to the SD events is calibrated using hybrid events, using the SD observable $S_{38}$ [24]. In a first step, one measures $S(1000)$, the integrated signal a 1 km from the shower core, interpolating a fitted lateral distribution function (LDF). The value of $S(1000)$ varies with the slant depth, and therefore with the incident zenith angle. Using the near isotropy of the incident cosmic rays, one can assume that showers at a fixed flux $I_0$ are equivalent, independent of the incidence direction. Selecting events such that $I(> S(1000)) = I_0$, one obtains curves of constant intensity in the signal-zenith angle plane. We use a particular curve $CIC(\theta)$ of that family, anchored at a median zenith angle of $\theta = 30^\circ$ to relate the signal $S(1000)$ at zenith
angle θ to the signal $S_{38}$ at 38° via $S_{38} = S(1000) CIC(38°)/CIC(θ)$. Using hybrid events which can be well reconstructed both by the FD and by the SD, one can fit the relation between $S_{38}$ and the energy to be

$$\frac{E}{\text{EeV}} = 0.16 \times \left( \frac{S_{38}}{\text{VEM}} \right)^{1.06}.$$  

The resulting spectrum is shown in figure 7. Systematic uncertainties in the energy estimate result in part from uncertainties in the fluorescence yield for EAS and in part in uncertainties in the correlation of FD and SD observables. At the highest energies, the spectrum terminates due to limited statistics. In the period until the middle of 2007, the data set of the Pierre Auger Observatory will increase by a factor 7, which will allow us to make measurements in the region of the GZK prediction.

**Anisotropy measurements**

Both AGASA [25] and SUGAR [26] report an excess of cosmic rays around 1EeV from the galactic centre region.

From the analysed data set of the Pierre Auger Observatory, SD events satisfying the quality trigger T5 [22, 23] were selected. The angular resolution is 2.2° for events with three SD stations and better than 1.7° for events with four or more stations [18]. The zenith angle of the events was limited to not more than 60°.
The coverage map (fig. 8A) was computed using a shuffling technique. Searches for a possible excess in the galactic centre region were done using the full Auger resolution of $1.5^\circ$ (fig. 8B), for a SUGAR resolution of $3.7^\circ$ (fig. 8C), and for an AGASA resolution of $13.3^\circ$ (fig. 8D), the last with a dataset reduced to the energy interval $1.0$–$2.5$ EeV. In all cases, the observed fluctuations are consistent with chance fluctuations of an isotropic distribution. This observations do not support the excesses claimed by AGASA or by SUGAR.

For a more detailed discussion of anisotropy studies, see [27–29].

**OUTLOOK**

The construction of the southern site of the Pierre Auger Observatory is well on its way and about to be finished in 2007. The first data set has been analysed and first scientific results are presented.

Once the observatory is completed, the data set will increase rapidly. We expect to have seven times more data to analyse by mid 2007, reducing our statistical errors significantly. This will allow us to perform studies of anisotropies and of spectral features, like the GZK prediction, with unprecedented detail.
FIGURE 8. Coverage map (A) and significance maps (B–D) for the galactic centre region. The straight line marks the galactic plane, the cross the galactic centre, the dashed line the field of view of AGASA. The circles indicate the regions of excess of AGASA and of SUGAR. Map B is smoothed for a 1.5° degree resolution, map C for 3.7° (SUGAR), and map D for 13.3° (AGASA).

Using our enlarged data set and independent detector studies, systematic and statistical uncertainties of the results will also be reduced. In particular, we expect to see the power of the hybrid technique demonstrated more clearly in the future.

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