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STATUS AND PERSPECTIVES OF THE PIERRE AUGER OBSERVATORY*

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The Pierre Auger Observatory is now being constructed to understand the nature and origin of cosmic rays at ultra-high energies ($> 10^{19}$ eV). It will be the largest cosmic ray detector ever built, covering 3000 square kilometers in both hemispheres in its full configuration. First data show a very good performance of the apparatus.

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1. Introduction

Cosmic ray particles with energies up to 3×10^{20} eV have been observed. At such high energies the protons, nuclei, or photons interact with various background radiation fields and should be strongly attenuated except if the sources are in our cosmological neighborhood (< 100 Mpc). This is the Greisen–Zatsepin–Kuzmin (GZK) suppression [1].

Furthermore, protons of ultra-high energies may point back to the source and open a new kind of astronomy with charged particles. The Lamor radius of particles with charge Z in a magnetic field B (in μG) is approximately given by $R_{\rm L} = 1$ kpc $\cdot\, E_{18}/(B_{\mu{\rm G}}Z)$, where the energy E_{18} is in units of 10^{18} eV. As $R_{\rm L}$ begins to exceed the size of the galactic disk for $E > 10^{18}$ eV, it is widely believed that cosmic rays below this energy are of galactic origin, driven by stochastic acceleration in supernova explosions. It is speculated that the so-called ankle at this energy may indicate the transition to a new, extragalactic component in cosmic rays.

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Three examples of experimental spectra at the highest energies are shown in figure 1, adapted from [2]. There is remarkable agreement considering the different detection techniques (scintillator ground array for AGASA and air fluorescence detection by one or two optical telescopes in HiRes I and HiRes Stereo, respectively). An energy scale error of maybe 20 percent is apparent. There are ongoing discussions about the energy calibration, aperture calculation, models of particle interactions and the possible existence of the GZK suppression. These issues will not be resolved by the present experiments and with the available data. I will show in this conference contribution that the Pierre Auger Observatory has the potential to find answers to these questions.

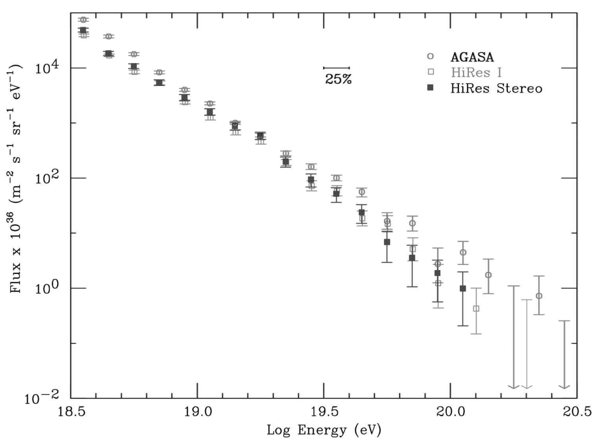


Fig. 1. Energy spectra reported by the AGASA and HiRes groups. The graphics is adapted from [2]; see text for comments.

There are indications that the average mass of cosmic ray particles becomes lighter with increasing energy. There is no indication for γ-induced events at 10^{20} eV. Fluctuations of the depth of maximum shower development in the atmosphere should be used with caution since atmospheric variations may play a significant role and were not accounted for so far [5].

The angular distribution of UHECR events is only known with insufficient statistics. At energies around 10^{18} eV the AGASA group reports an excess of events coming from the galactic plane. At the highest energies there are some double or multiple events within the angular resolution but much more data are needed before strong conclusions can be made.

Details on cosmic ray properties and the experimental data may be found in excellent recent reviews by Nagano and Watson [4] and by Cronin [2].

2. The Pierre Auger Observatory

2.1. Motivation and concept

The scientific objectives of the Pierre Auger Observatory are to understand the nature, origin and propagation of ultrahigh-energy cosmic rays. The questions addressed include:

- What is the origin of UHECR — acceleration of charged particle or decays of supermassive relic objects?
- Is there any evidence for anisotropies in the distribution of arrival directions?
- Does the energy spectrum exhibit a GZK-like suppression feature?
- Are there point sources?
- What are the primary particles?

To answer these questions, the Auger Observatory is designed for full-sky coverage above 10^{19} eV with an aperture of 7350 km^2sr in each hemisphere, calculated for zenith angles up to 60°. The Pierre Auger Collaboration consists of more than 250 scientists from Argentina, Australia, Bolivia, Brasil, Czech Republic, France, Germany, Italy, Poland, Mexico, Slovenia, Spain, United Kingdom, USA and Vietnam. The full current author list and many technical details can be found at the Auger internet portal [3].

Construction of the Southern site started in 1999 in the Province of Mendoza, Argentina. The observatory campus is located in the city of Malargue at the South–West border of the detector field. In the final configuration 1600 water tanks will be placed on a triangular grid with 1.5 km spacing to cover 3000 km^2. Twenty-four fluorescence detectors in total will be grouped in four locations at the perimeter of the ground array to oversee the entire surface detector. In figure 2, each dot represents one water Cherenkov detector. The four telescope stations are placed on small elevations called LEONES, COIHUECO, MORADOS and AMARILLA. The fields of view for the telescopes are indicated.

Table I gives the expected number of events per year for the full configuration assuming the AGASA energy spectrum. The hybrid detection technique combines the statistical power of a ground array with calorimetric energy measurement and detailed longitudinal reconstruction for a 10% subset of showers recorded during clear, dark nights. The energy threshold of the fluorescence telescopes is lower than that of the surface array, yielding more low-energy events. The hybrid Auger detector is sensitive to the primary particle type by exploiting the atmospheric depth in which the shower maximum occurs, the ratio of muons to electrons in the shower, and the time structure of the shower disk.

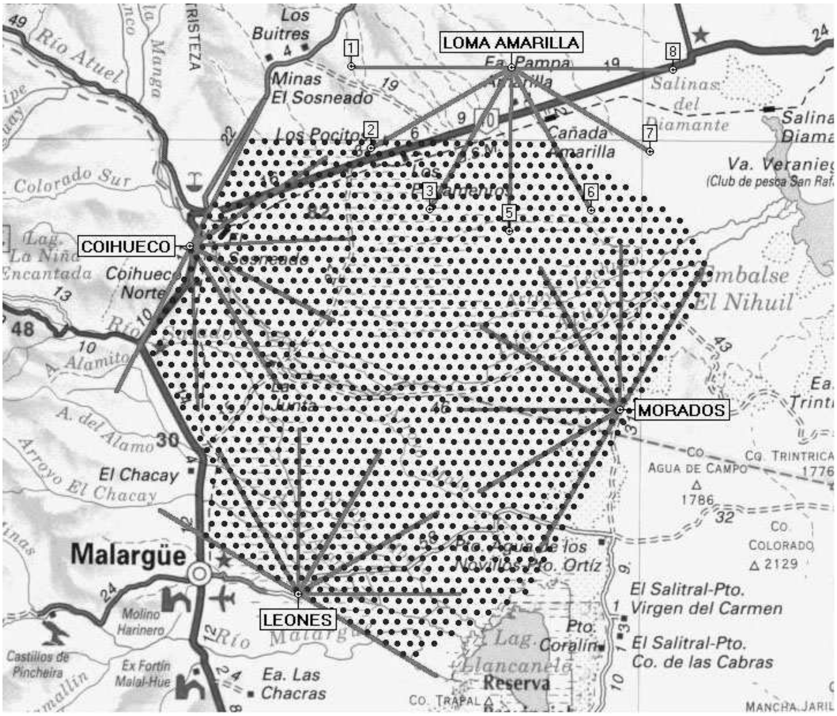


Fig. 2. Location and layout of the Southern Pierre Auger Observatory in Mendoza, Argentina.

TABLE I

Expected events per year in the Pierre Auger Observatory for events up to 60° zenith angle assuming a spectrum as suggested by the AGASA results.

energy [eV]	SD alone	FD
$> 10^{18}$	16000	30000
$> 10^{19}$	5200	520
$> 10^{20}$	100	10

Large detectors for cosmic rays have also a significant detection potential for neutrinos, which may be distinguished from other primary particles as very inclined showers occurring deep in the atmosphere above the detector. The thickness of the atmosphere is 36,000 g/cm^2 for a horizontal path (90° zenith angle) and only neutrinos can travel through most of this matter before they induce an extensive air shower near the detector. Neutrino-induced showers would exhibit a curved shower front structure whereas ordinary, hadron-induced showers have a thin, flat muonic disk after traversing several atmospheric depths.

The Pierre Auger Observatory may detect neutrino fluxes at levels similar to that of the IceCube detector, but at higher energies [9, 10].

2.2. The surface detector (SD)

The Surface Detector (SD) is made of water Cherenkov tanks. The tanks have 3.6 m diameter and 1.2 m height to contain 12 m^3 of ultra-clean water viewed by three 9” photomultiplier tubes (PMT). Solar panels and a buffer battery provide electric power for the local intelligent electronics, GPS synchronization system and wireless LAN communication. The analog signals are continuously digitized with 15 bit dynamic range at 40 MHz sampling rate and temporarily stored in local memory.

Fig. 3. Left: four tanks aligned along the picture diagonal. Right: a single tank in the Pampa.

Muons produced in the atmosphere provide a well-understood and uniform background across the whole of the surface array. The signal from a muon traversing a Cherenkov tank is proportional to the geometric path length, providing the basis of the calibration. The peak due to single muons crossing a tank is clearly visible in the histogram of pulse heights from a photomultiplier, see figure 4. The position of this peak is an important calibration parameter. It corresponds to about 80 photoelectrons.

Photomultiplier calibration is carried out in three steps. Firstly, the three photomultiplier tubes are matched by gain by adjusting their voltages so that the rates (about 100 Hz) above a threshold of 3 vertical equivalent muons (VEM) are the same. Secondly, the evolution of the gains is monitored and inserted into the data flow. Finally, the absolute calibration is determined from a sequence of measurements made on an identical test tank located at the central campus.

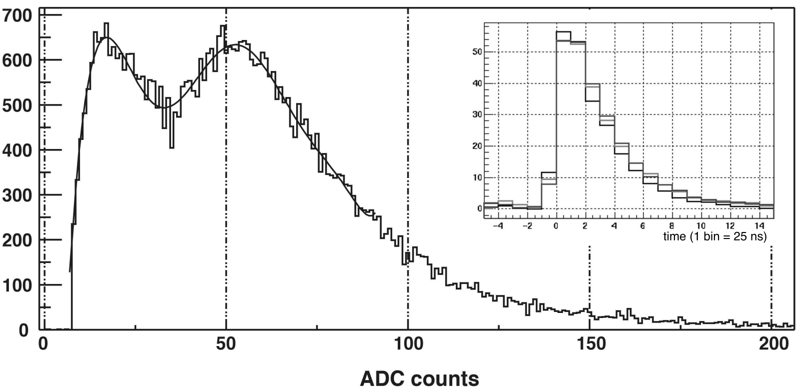


Fig. 4. Total charge distribution on one photomultiplier. The peak at 50 ADC counts is due to single muons passing the water and establishes 1 VEM as a signal unit. The inset shows well balanced FADC muon traces for three photomultipliers in a tank.

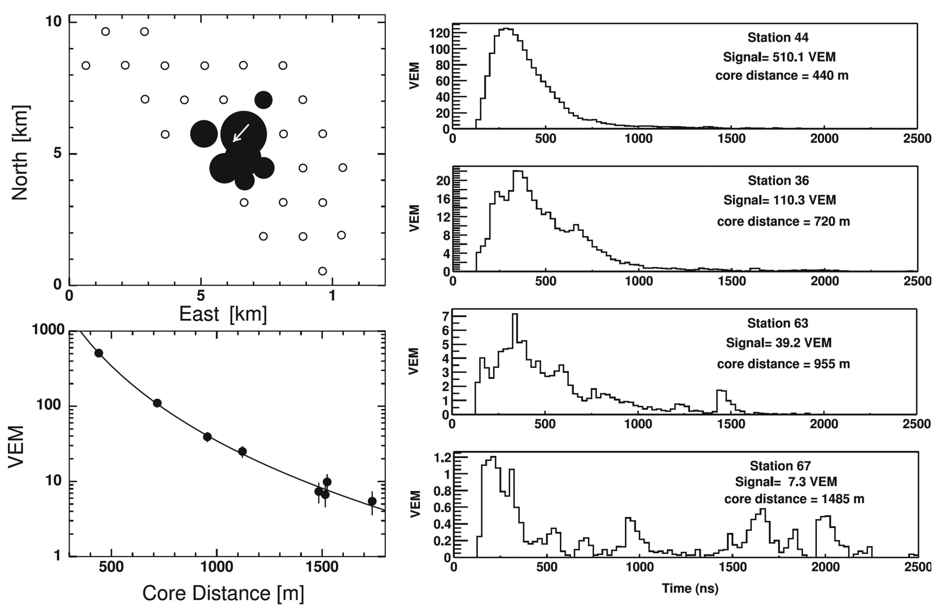


Fig. 5. Example of a typical event (no. 255146) with about 5×10^{18} eV detected in the engineering array. Top left: The EA seen from above with the 8 triggered tanks; pulseheights are logarithmically represented by area. Lower left: lateral distribution appropriate for a shower at 25 degrees zenith angle. Right: FADC traces for four selected stations.

The trigger conditions will require four or five stations with a significant energy deposit. Initially 1.75 VEM are required in a threefold coincidence, or less pulse height spread over up to 3 μs. Detection efficiency begins around 10^{18} eV and reach 100% at 10^{19} eV. The multiplicity of hit tanks during the initial test phase is shown in the next section.

In figure 5 we show the geometry, lateral distribution and FADC traces of an event recorded in the surface detector. It is worth noting that the time structure of PMT pulses carries rich information related to the mass of the primary particle.

2.3. The fluorescence detector (FD)

The Fluorescence Detector (FD) consists of 24 wide-angle Schmidt telescopes grouped in four stations, see figure 2. Each telescope has a 30° field of view in azimuth and vertical angle. The four stations at the perimeter of the surface array consist of six telescopes each for a 180° field of view inward over the array. Each telescope is formed by segments to obtain a total surface of 12 m^2 on a radius of curvature of 3.40 m. The aperture has a diameter of 2.2 m and is equipped with optical filters and a corrector lens. In the focal surface a photomultiplier camera detects the light on 20×22 pixels. Each pixel covers $1.5^\circ \times 1.5^\circ$ and the total number of photomultipliers in the FD system is 13,200. Part of the interior of the FD station Los Leones is shown in figure 6.

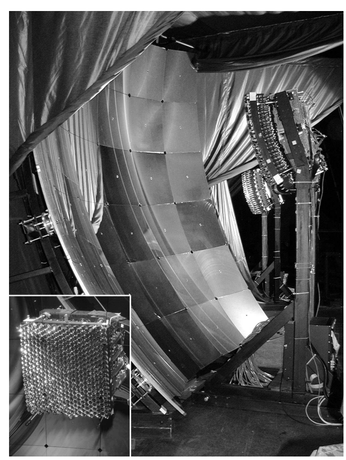


Fig. 6. Left: the Los Leones telescope building. Right: fluorescence telescope exhibiting the segmented mirror and the PMT camera.

PMT signals are continuously digitized at 10 MHz sampling rate with 15 bit dynamic range. The FPGA-based trigger system is designed to filter out shower traces from the random background. The First Level Trigger system performs a boxcar running sum of ten samples. The trigger is fired if the sum exceeds a threshold . This threshold is determined by the trigger rate itself, and is regulated to keep it close to 100 Hz. Every microsecond, the camera is scanned for patterns of pixels that are consistent with a track induced by the fluorescence light from a shower. This is the Second Level Trigger, which has a rate of 0.3 Hz. It is dominated by muons hitting the camera directly and random noise. These components, as well as lightning, are then filtered by the software Third Level Trigger, yielding a rate of one event every 20 minutes per telescope. The two telescopes were operated during dark periods at 11% duty cycle as expected.

The online event display in figure 7 shows a projection of the camera image; hit pixels are indicated on the camera and raw FADC data are shown for selected pixels.

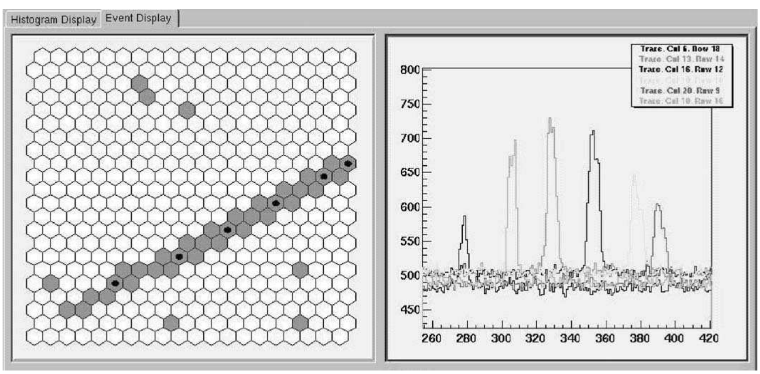


Fig. 7. Online display of an event in the FD.

Great attention is given to the atmosphere being an integral part of the fluorescence detector. The monitoring system uses laser beams, LIDAR, calibrated light sources and continuous recording of weather conditions. The sensitivity was estimated to be 10 EeV at 26 km distance. Using a YAG laser of adjustable pulse energy, we have verified that the FD meets the trigger sensitivity required to record 10^{19} eV showers throughout the SD aperture under normal atmospheric conditions.

The fluorescence detectors were preliminary calibrated and atmospheric corrections were evaluated, including a subtraction of Cherenkov light in an iterative procedure, see figure 8.

The track reconstruction in a stereo configuration or in a hybrid configuration together with a ground array is greatly improved compared to a

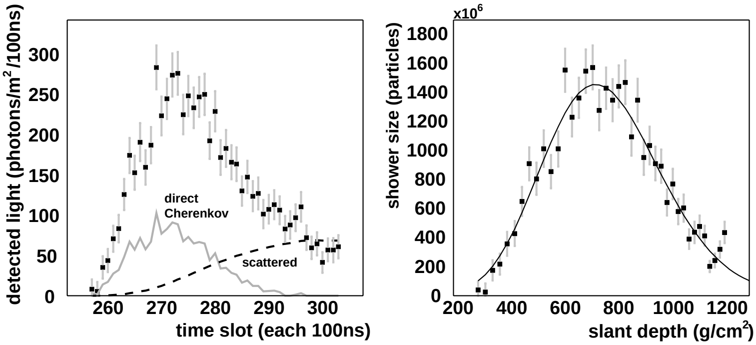


Fig. 8. Reconstruction of the fluorescence light curve subtracting the direct and scattered Cherenkov light (left). The right panel shows the final profile.

monocular reconstruction, see figure 9. In a monocular detector, the angle within the shower-detector plane is difficult to obtain from the variation on angular speed. Stereoscopic and/or hybrid operation with just a single ground detector (indicated by three ellipses) greatly improves the reconstruction. Even a single tank hit removes the degeneracy in the track fit parameters efficiently.

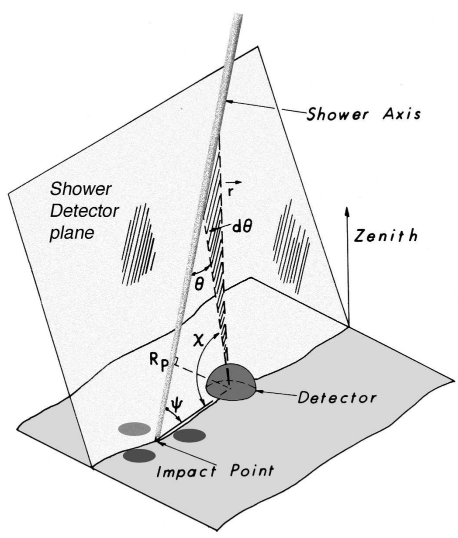


Fig. 9. Geometry of shower reconstruction; see text for explanations (adapted from Fly's Eye, 1985).

2.4. Results from the Engineering Array

The Engineering Array (EA) consisting of 40 water tanks and 2 prototype telescopes was built to demonstrate the hybrid concept and to validate the technical designs before mass production.

For the SD the construction and operation of the EA has allowed the testing of tanks (materials, liners, solar panels, brackets, cabling, *etc.*), as well as of the deployment strategy, water production and quality, photomultiplier tubes, electronics, triggers, software and data acquisition, monitoring packages, telecommunications.

For the FD it has been possible to evaluate the performance of the optics, mirrors, electronics, corrector plates, filters and shutters with two prototype telescopes in the Los Leones building.

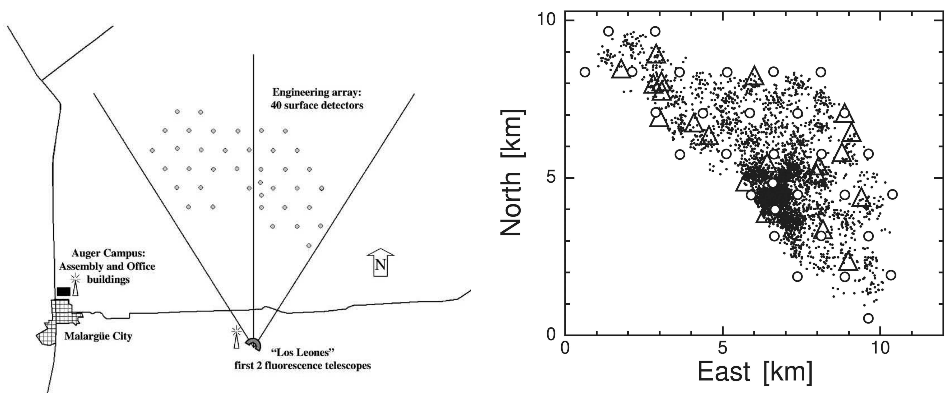
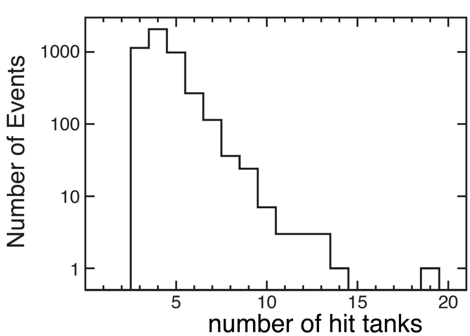


Fig. 10. Left: Layout of the Engineering Array with 32 fully instrumented tanks. The lines indicate the 30 degrees wide field of view of the fluorescence telescopes. Right: Reconstructed core locations of a sample of showers, see text.

The location of the SD Engineering Array has its center 10 km north of the FD building at Los Leones. Forty detector tanks were deployed, of which 32 were completely instrumented. 37 of these detectors were positioned on a triangular grid, covering an area of approximately 46 km^2. The distance between neighboring detectors is usually 1.5 km. The mean and maximum position deviation of these tanks are 21 m and 90 m, respectively. Near the center of this array, a further detector was placed 11m from an existing one. This pair of detectors enables comparisons of timing and density measurements to be made at essentially the same distance from the shower core. Additionally, two detectors were deployed at the middle of two of the triangles of the detector pair, *i.e.* at 860 m from their three nearest neighbors, allowing triggering on lower energy showers. The SD time synchronization using GPS works well within 50 ns and the angular resolution is the order of 1° or better. Figure refealayout shows the geometry of the Engineering Array and the reconstructed core locations of a sample of showers. In this plot the 32 active stations are represented by circles. Each dot indicates a low-energy event whereas triangles indicate events above 10 EeV. The accumulation due to the infilled portion of the array is visible.

The ground array and fluorescence detectors were commissioned with the distributed, asynchronous data acquisition system from December 2001 onwards. During four months, the EA was operated continuously. It recorded several thousand events in either subsystem and about 70 hybrid events. The multiplicity distribution of triggered tanks is shown in figure 11 for physics events selected by a preliminary analysis procedure described in [6]. The highest multiplicities are given by very inclined events; when the two adjacent detectors were triggered, only one hit was counted. In the same figure we show the declination distribution of showers with energies in the range 1.0–3.0 EeV and zenith angles $< 60°$. For these events, due to the thick water Cherenkov detectors and the good muon detection, the FWHM of the declination distribution is about 75°, which is much broader than for a thin scintillator array at the same altitude ($\approx$ 1400 m a.s.l.).



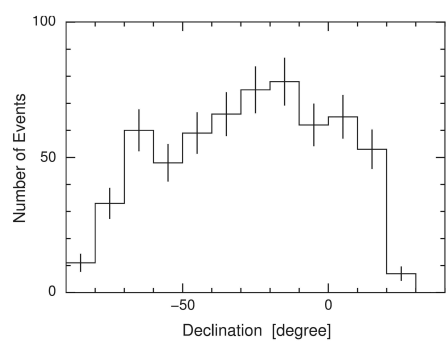


Fig. 11. Left: Multiplicity distribution of triggered tanks. Right: Declination angles of showers.

The power of hybrid operation is seen in figure 12, which exhibits a direct measurement of the lateral distribution with small hybrid events. We show here the energy in the SD in VEM divided by the fluorescence energy in EeV as a function of distance from the shower axis in the shower plane. In most cases only one tank contributed to an event. The vertical errors reflect the uncertainty in the VEM measured from the FADC trace due to fluctuations and preliminary calibration. The horizontal error of ± 50 m is the uncertainty of the tank to shower axis distance reconstructed from the FD. We expect abundant hybrid data in the near future as the array grows towards the fluorescence telescope stations.

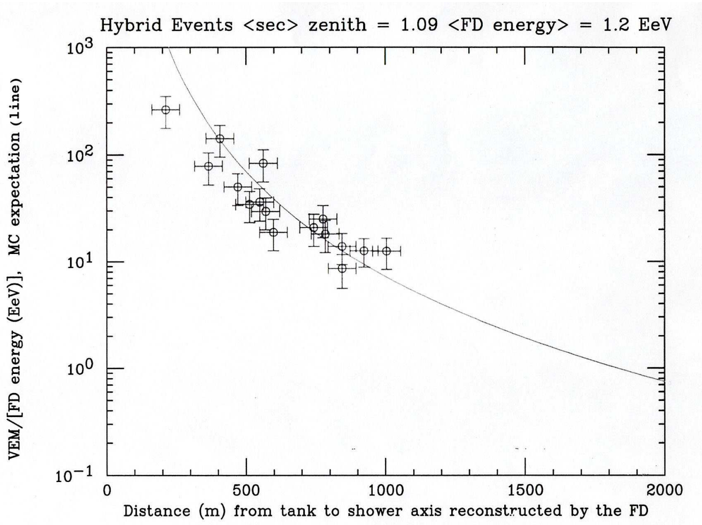


Fig. 12. The lateral distribution of showers is probed with hybrid events. The line is the expectation based on simulation.

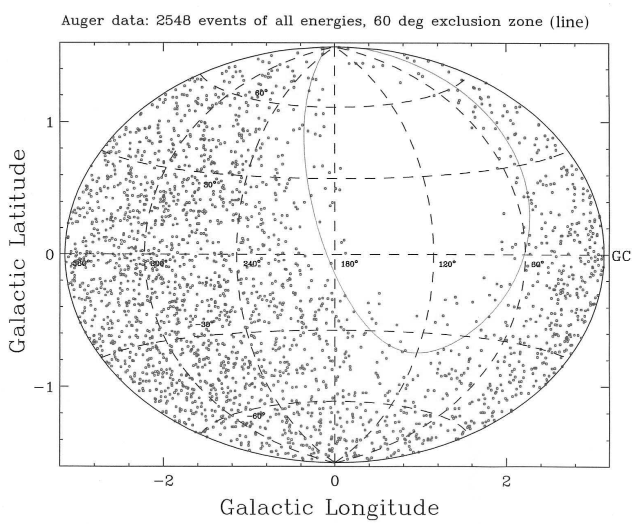


Fig. 13. Arrival direction distribution of the Auger EA events in galactic coordinates. The galactic center is at the edge of the diagram. The line shows the exclusion zone for a zenith angle of 60 degrees.

The successful initial operation of the Southern Auger Observatory is also demonstrated in figure 13 representing a map of the arrival directions of 2500 events of all energies.

3. Completion of the Southern Auger Observatory

The prototype apparatus has met or exceeded all our specifications. We are thus confident to proceed with the construction of the full-scale observatory.

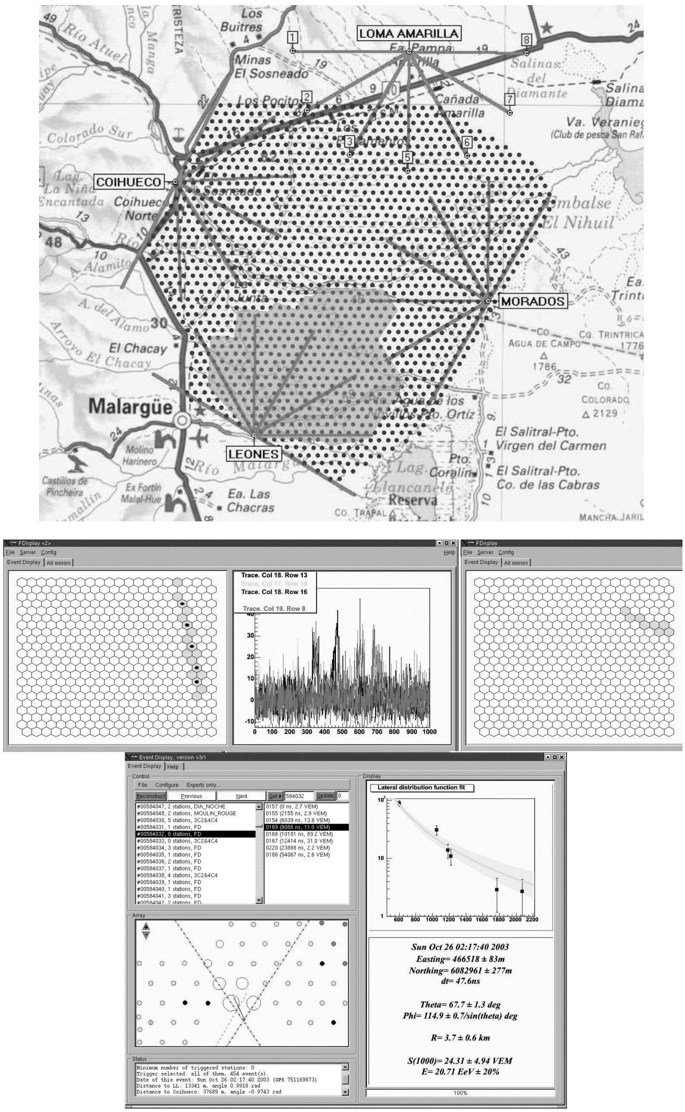


Fig. 14. Top: As of April 2004 tanks have been deployed in the shaded area. Bottom: The first hybrid-stereo event recorded simultaneously in the fluorescence telescopes at Coihueco (bottom) and Los Leones, and in several ground detectors.

Tanks are being deployed at a regular rate, filled with distilled water and electronic packages are installed rapidly. At the time of writing (April 2004) there are 300 detectors operational out of 375 deployed, located in the shaded area of figure 14. Two buildings for fluorescence telescopes at LEONES and COIHUECO, indicated in figure 2, are completed and equipped with 6 and 2 telescopes of the final design, respectively.

Hybrid operation of the surface array together with both the Los Leones and Coihueco telescopes has resumed, and first hybrid-stereoscopic events have been detected during October 2003. The event shown in figure 14 has been seen from Coihueco at a distance of 37km and 8km from Leones. The reconstructed zenith angle is $68°$ and the energy estimate is 2×10^{19} eV.

To utilize the full potential of the calorimetric fluorescence measurement, absolute calibration and careful atmospheric measurements are necessary. We make use of LIDAR equipment for atmospheric profiling and employ fixed vertical and steerable lasers at the array center for atmospheric monitoring, timing and calibration checks. There are continuous horizontal attenuation measurements as well as balloon born atmospheric measurements.

Special efforts are being made to determine the air fluorescence efficiency and its dependence on relevant conditions. Such efforts are actually carried out in several experiments and collaborations, for which I refer the reader to the AIRLIGHT 03 workshop, which was held in December 2003 at Burg Liebenzell, Germany. [12].

Construction of the third telescope building, Los Morados, has started. In March 2004 the communications equipment at this location was commissioned including the backbone microwave link to Los Leones. Parallel to detector deployment and telescope installations, the observatory continuously records cosmic ray events. By the end of 2004, a data set comparable to the entire collection of the AGASA experiment is expected. The full configuration of the Southern site will be reached by 2005.

3.1. The Northern Auger Observatory

Full-sky coverage is important to interpret the expected data on ultra-high energy cosmic rays. The extreme cases are that point sources or an isotropic distribution will be found, with or without a GZK cut-off. The astronomical features of the Northern and Southern hemispheres are very different, see figure 15 where we show the matter distribution in the distance range between 7 and 21 Mpc. Therefore, observations in one hemisphere cannot be extrapolated to the other one and a complete survey must be done.

After completion of the Southern Auger Observatory, it is planned to commence construction of the Northern Auger Observatory. The selected

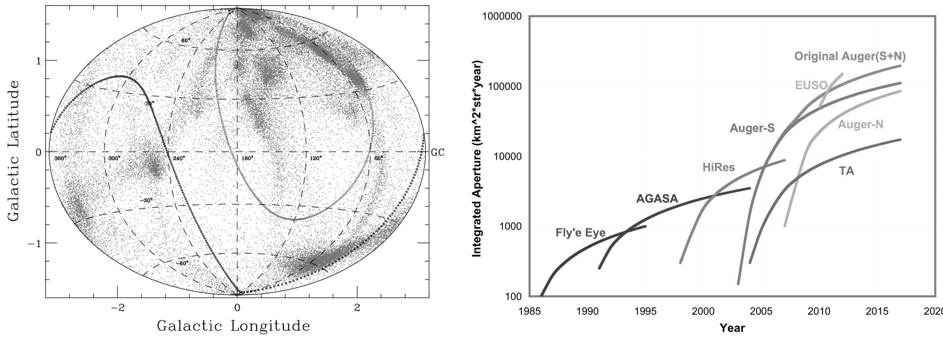


Fig. 15. Left: Distribution of gravitating matter in galactic coordinates in the distance range 7-21 Mpc. The dot density is proportional to the column density of matter in each direction. Invisible zones are indicated for observatories located in the Northern (left line) and Southern hemispheres (right line) [7]. Right: Integrated exposures of UHECR experiments [8].

site is in the USA in Millard County, Utah or in Colorado. Seamless data integration of both sites is important, therefore the baseline layout of the Northern observatory will be similar to that of the Southern site. We show the integrated exposures of UHECR experiments in the right-hand part of figure 15, where the lines for the Auger Observatory correspond to two identical sites of 3000 km^2 each. Extensions and the use of new technologies are under consideration.

Based on our very positive experience with the fast-growing Auger Observatory in Argentina, we are confident to make significant steps towards a better understanding of ultra-high energy cosmic rays in the next few years.

All members of the Auger Collaboration have been working together to make this possible.

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