COURSE 1

PIERRE AUGER OBSERVATORY: STATUS AND PROSPECTS

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PHOTO: height 7.5cm, width 11cm
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PIERRE AUGER OBSERVATORY: STATUS AND PROSPECTS

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Abstract
The Pierre Auger Observatory is the next generation ground based cosmic ray detector fully devoted to the study of the ultra-high energy cosmic rays (UHECR) with energies above \(10^{19}\) eV. The Auger Observatory, with its unique features (unprecedented statistical power, hybrid detection possibilities, full sky aperture, excellent sensitivity for all zenith angles...), will bring in a decisive step, if not definitive answers, in the understanding of one of the most puzzling phenomena of modern astrophysics.

1 Introduction
For its designers and builders, the Auger Observatory is the best (and for the time being, unique) tool to unveil (conclusively?) the mystery of the origin and/or nature of the UHECR. Let us give a few arguments in favour of such a presumptious statement. When completed, i.e. with a site in each hemisphere, the Observatory can be considered as a single detector having a full sky coverage, an almost compulsory feature to be able to study weak anisotropies (e.g. for sources accumulating in the galactic halo). The detector is “hybrid”, meaning that some 10% of the events will be observed both with a ground array and a fluorescence telescope2. This unique feature improves the detector’s performance in many aspects: cross-calibration of the two components, improving the energy and angular resolution; two independent methods for the reconstruction of the air-shower (and hence a weaker dependence on models used for simulation); an increased number of observables related to the incident cosmic ray’s nature, therefore a stronger

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2This article will be restricted to the parameters and performances of the ground array.

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lever to study the chemical composition (e.g. by a multi-dimensional analysis), etc. The use of Cherenkov tanks rather than scintillators for the ground array increases the angular acceptance to values much larger than the usual 60°. Actually, showers with zenith angles up to 90° can be detected. The specific case of tau neutrinos and angles even larger than 90° is mentioned in Section 3.4 [1]. This allows the opening of a new window for UHE neutrino astronomy, in an energy range where the Earth becomes opaque to neutrinos and makes life harder for underwater or under-ice neutrino telescopes. Finally, maybe the most important performance needed for this physics is the necessary statistical power. Large statistics are needed for good spectrum reconstruction (a necessary indicator of the operating production mechanism), anisotropy studies and chemical composition studies. The complete Auger observatory, with its two sites, will have an aperture of more than 14,000 km² sr, nearly two orders of magnitude above the largest operating ground array (AGASA) and 15 to 40 times that of the most powerful existing fluorescence detector (HiRes).

2 Main parameters of the Ground Array

The full Auger Observatory will consist in two sites of 3000 km² each. The ground array stations are to be distributed with a regular spacing of 1.5 km over sites whose shape has to be adapted to the undulations and access conditions of the field. The two sites were chosen on the basis of a list of specifications of which the most important were the size (and flatness of the landscape for easier wireless communication), the latitude (between 35 and 40° North and South for optimum sky coverage), the altitude (around 1400 m, an altitude close to the shower maximum for a vertical shower to minimize statistical fluctuations), dry atmosphere, clear skies and low light pollution for the optical component (and partly for the solar power). After two years of prospecting, the choice was the following. Northern site: Millard County, Utah, U.S.A. (39.1° N and 112.6° W); southern site: Malargüe, Mendoza, Argentina (35.2° N and 69.2° W). A prototype observatory called the engineering array (EA) is already built on the southern site (see below).

Detector stations. Each surface detector is a 3.6 m diameter, 1.2 m high roto-molded plastic tank, filled with filtered and de-ionized water. The internal walls of the tank are lined with a highly reflecting and diffusing material (Tyvek). The charged particles (mainly electrons – including those from Compton scattering and photon conversion – and muons) produce Cherenkov light in the water that is detected by three phototubes installed on the top of the tank.
The electrical power of the station is provided by solar panels.

The electronics and gains of the phototubes are designed so that one can collect signals as close and as far as possible from the shower core (e.g. from 1 to \(10^5\) photoelectrons in a 25 ns time slot) without requiring a too sophisticated system. The linear gain range of the photo-multipliers (PMTs) is required to be \(10^5–10^6\) (with an operational value of \(2 \times 10^5\)). Each of the three PMTs has two outputs, one (with a low gain amplification) from the anode, another (with a high gain amplification) from the last dynode. The outputs are read with six 10-bit flash-ADCs cycling with a frequency of 40 MHz.

This allows data at distances from the core of the expected highest energy showers in the range of 500 m to several kilometers to be recorded.

Communications. Data from the detector stations are transferred to the CDAS (Central Data Acquisition System) in a two-step process. The first step is the communication between the local stations and base station units (BSU) installed on collector towers situated near the fluorescence detector (FD) buildings (in principle, four of them). The BSUs then transfer the data through a microwave link to the CDAS.

3 Global performance of the ground array

3.1 Aperture

Based on a total area of 3 000 km\(^2\), the aperture of the Auger ground array is (for one site) 7350 km\(^2\) sr, when we take 60\(^\circ\) as the maximum zenith angle. Since, as was stated in the introduction, a Cherenkov tank is sensitive to particles penetrating its volume at any angle, the value given here can be considered as a lower limit. However, one should keep in mind that showers with very large zenith angles will be difficult to fully analyze in a model independent way (see below).

3.2 Energy resolution

Below 60\(^\circ\), the energy resolution is weakly dependent on the energy and zenith angle. As the energy increases from 10 to 100 EeV or more, its rms value is expected to slightly improve from 12 to 10\% or less\(^1\). This result is almost independent on the nature of the primary particle, with slightly better resolution for showers generated by heavy nuclei because of smaller shower-to-shower fluctuations. At larger zenith angles, the electromagnetic component of the shower is more or less totally absorbed and for the energy

\(^1\)To be strict, this error does not include part of the systematic errors coming e.g. from the shower model adopted.
measurement one has to rely mainly on the lateral distribution function for penetrating muons. Therefore, in this range we expect the systematic errors due to hadronic modelling to dominate.

### 3.3 Angular resolution

The measurement of the incident cosmic ray’s angle is made by fitting an adapted surface (paraboloid) to the shower front reconstructed from the arrival time of the particles on the array stations. This of course is a totally model-independent measure, and the precision on the angles depends on a few parameters: the number of stations hit by the shower front particles, i.e. the projection of the front on the ground (which depend on the zenith angle and the primary energy); the fluctuations on the arrival time of the particles (therefore the thickness of the shower front); the precision on the relative synchronization of the detector stations (the interpolated and corrected GPS time). The average angular resolution\(^2\) for a hadronic shower at 30° for all energies in the detector’s optimum energy range (>10 EeV) is about 1°. This is obtained with a timing precision of about 15 ns (GPS time interpolated with a 100 MHz clock). This resolution improves with the energy (≃0.5° at the same angle above 100 EeV), and with the incident angle (≃0.3° at θ = 80°, all energies).

### 3.4 Composition analysis

The number of known stable particles that can propagate over large distances and then be detected on earth are quite limited in numbers: nuclei (heavy or light, with special emphasis on protons), photons and neutrinos. In the search for a solution to the UHECR puzzle, several authors invoke exotic particles or interactions (meaning not yet established with experimental evidence). Such models have called for mechanisms which would violate the GZK cutoff. Examples are: neutrinos whose cross-sections on nuclei are substantially increased by graviton exchanging interactions [4]; vortons [5] (stable, superconducting cosmic string loops); magnetic monopoles [6], and so on. Here we shall limit our comments to standard particles and interactions.

Different particles leave different fingerprints on the EAS parameters. Two such parameters are the position of the shower maximum \(X_{\text{max}}\) and the relative muon content of the shower at ground level (which of course depends on the slant-depth \(X = X_0 / \cos \theta\) where \(X_0\) is the vertical atmospheric depth at the altitude of the detector). The shower maximum can be

\(^2\)All the values given here for the angular resolution mean the uncertainty which contains 68% of all events.
measured directly by the fluorescence detector. Only the ground array can measure (to some extent and at large distances from the shower core) the muon content by the analysis of the flash-ADC traces. Other indicators such as the shower front curvature, rise time of the signal detected by the array stations, steepness of the lateral distribution functions (LDF) are parameters to use in a multi-dimensional analysis of the nature of the primary cosmic ray. However, all simulation and reconstruction studies show that the discrimination between heavy and light nuclei (the most likely ones to be found in the incident samples being iron nuclei and protons) will be possible only on a statistical basis. This is due to physics: the depth at which the shower maximum occurs (and the parameters which derive from it and are measured by the ground array) is a strongly fluctuating parameter and its values, even for extreme cases such as protons and iron nuclei, have such an overlap that only their average over large numbers will be distinguishable.

The situation improves dramatically for gammas and neutrinos, strong signatures of exotic processes (top-down mechanisms) if found in large proportions at extreme energies.

The identification of UHE gammas is based on two physical phenomena: photon conversion in interactions with the geomagnetic field and the LPM effect. Gamma rays with energies $E_\gamma$ propagating through a magnetic field with a transverse component $B_\perp$ have a large probability of converting into electron-positron pairs if the product $E_\gamma B_\perp$ is large. This happens in particular for $E_\gamma > 10$ EeV for typical values of the geomagnetic field. The conversion occurs at altitudes of several thousands kilometers (therefore well above the atmosphere). The $e^+e^-$ pairs then undergo energy loss by magnetic bremsstrahlung and so on. By the time the secondary electrons and photons reach the atmosphere, they all have energies less than a few EeV. The development of this pre-shower in the atmosphere is like that of a superposition of several low energy electromagnetic showers.

However, whenever the incident gamma arrives with its direction parallel to the field vector, the conversion becomes negligible and the gamma penetrates the atmosphere with its full energy. Then a second phenomenon, the Landau–Pomeranchuk–Migdal (LPM) effect, takes over. This effect consists of a decreasing of the cross-sections of electromagnetic processes with the energy of photons/electrons and the density of the propagation medium. It becomes dominant over the Bethe–Heitler processes for particles with typical energies of around 100 EeV even in the rarefied layers of the upper atmosphere.

Figure 1 shows how these effects operate [8] at a given place, namely at the site of the southern Auger Observatory. One can see how the gamma conversion probability depends on the energy of the photons and their direction in the earth’s reference frame. The dashed circles show the directions...
Fig. 1. Photon conversion probabilities as a function of the direction in the earth’s frame of reference as seen from the southern Auger site [8]. The conversion probabilities range from 100% (black areas) to 0% (white zones).

with zenith angles of 30 and 60 degrees. One can see that for all values of the gamma ray energy, the conversion probability is zero in a direction close to 50° North. UHE gammas coming from this direction will deeply penetrate the atmosphere before starting to shower. Therefore their geometry compared to those coming from the other directions will be quite distinctive and detectable.

With the use of the curvature, as well as the steepness of the LDF or the muon content of the EAS, it is expected that a 5–10% contamination by UHE photons of a sample of protons will be detectable.

The detection of neutrinos in the same energy range with a ground array is based on the fact that a particle penetrating the atmosphere tangentially to the earth will encounter an enormous amount of matter [10]: more than 800 radiation lengths, about 350 nuclear interaction lengths. For horizontal airshowers (HAS) the atmosphere absorbs all particles except neutrinos and muons. Using cross-section values extrapolated from lower energy data [9],
the probability that UHE (anti)neutrinos interact in such a thickness of air is larger than $10^{-4}$ above 0.1 EeV, which is far from being negligible. Moreover, this energy range is just above the limit accessible to the neutrino telescopes for up-going neutrinos, since above $10^{16}$ eV the earth becomes opaque to them. It was therefore interesting to see what a giant ground array such as Auger can do with the detection of UHE neutrinos. The studies are based on EAS incident with a zenith angle above 75 degrees and energies between 0.1 and 100 EeV. For neutrinos above 1 EeV, the acceptance of the ground array is more than $10^3$ km$^2$ water equivalent. The background to the expectedly weak neutrino signal is of course the numerous hadronic showers incoming at large angles. However, making use of the same methods as in the case of UHE gammas (in particular the shape of the shower front and the signal risetime) it is expected that even a few neutrino events per year should be detectable.

An equally interesting case is that of the tau-neutrinos if neutrino oscillations as observed by Super-K and SNO are confirmed. With a maximum mixing, and given the large propagation distances, it is expected to have equal proportions of the three neutrino species incident on earth, if the $\nu_\mu/\nu_e$ ratio at the source is 2/1. In this case, it becomes very interesting to look for tau neutrinos through their interaction in the ground (i.e. with zenith angles larger than $90^\circ$) producing a $\tau$. In our energy ranges, the taus can propagate over tens of km before decaying (or interact with the earth and start an iterative process). If the decay occurs in the volume of air above the ground array, the direction of the showers could, at least statistically, give indications to discriminate them from the “standard” HAS.

Detailed studies were made [1, 11] to estimate the performance of the Auger ground array with respect to neutrino detection. Figure 2 is a summary of recent studies where the sensitivity for one event per year per decade of energy is shown for $\nu_\mu/\nu_e$ (top thick line) and $\nu_\tau$ (shaded area). The curves limiting the shaded zone on this figure are for deep-inelastic scattering with strong energy loss (top) and no such loss (bottom). The expected event rate depends of course on the models of UHE neutrino production. Whenever the sensitivity curve remains below the flux curves for more than one decade of neutrino energy, more than one event per year is expected to be observed. For models considered as being solid [12], such as the so-called GZK neutrinos (those produced as secondaries of the interactions of UHECR with the 2.7 K microwave background, full line on the figure) the detection rate appears to be rather low. For more speculative estimates (GRBs, AGN etc.) several events per year should be detected. The horizontal line shown as the “$\nu_\tau$ limit” is the 90% confidence level limit (background-free detection) achievable with five years of data taking with Auger for an $E^{-2}$ flux between 0.3 and 3 EeV.
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Fig. 2. Sensitivity of Auger to neutrino detection [1]. The $\nu_\mu/\nu_\tau$ flux estimates are from [12] and are divided by a factor 2 to take into account the full mixing hypothesis. See text for comments.

4 Status and prospects

The Collaboration decided to phase the construction of the southern site in two steps. During 2001, the prototype hybrid system called the Engineering Array (EA) was built. It consists of 40 tanks covering an area of about 50 km$^2$ and two elements of fluorescence telescopes overlooking the area equipped with the tanks. The EA aims to test all the technical issues (including those where the final choice is still open) before the launching of the final production. The deployment of the full observatory is expected to be completed by the end of 2005.

The data presented here come from unnumerable sources within the Auger collaboration. Those who provided this information will know that my deep gratitude goes to them. A special thanks to Murat Boratav who helped me in the writing of this lecture.

References