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THE PIERRE AUGER OBSERVATORY: STATUS AND RECENT RESULTS

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Abstract. The Pierre Auger Observatory is the new generation facility for the ultra-high energy cosmic rays (UHECR, $\geq 10^{17}$ eV) studies. The project aims at large aperture (> 7000 km^{2}sr above 10^{19} eV) hybrid detection (combining air fluorescence and ground particle techniques) of the highest energy cosmic rays with the full-sky exposure (with 1 site per hemisphere). The Southern Auger Observatory in Argentina is nearing its completion. First results on the UHECR anisotropies search, and on the energy spectrum are discussed.

1 Introduction

After more than 40 years since the first detection (1962) of a cosmic ray event with energy reaching 10^{20} eV, the nature and origin of the ultra-high energy cosmic rays are still unknown. At these extreme energies, potential astrophysical acceleration sites list is limited to objects like active galactic nuclei, gamma-ray bursts or galaxy clusters (Nagano & Watson 2000). In more exotic scenarios these highest energy cosmic rays are produced in interactions or decay of the primordial Universe relics such as topological defects or super-heavy dark matter.

If the standard acceleration scenario with the nuclei arriving from sources at cosmological distances holds, it is expected that the cosmic ray flux should undergo a strong suppression (so-called GZK cut-off) at energies above $10^{19.7}$ eV. This spectral break corresponds to the effective threshold of pion production in the interaction of the UHECR protons with the CMB radiation. At similar energies, nuclei photo-dissociate on the CMB. As a consequence, the horizon of the UHECR sources in the standard scenarios is restricted to our local "neighbourhood" ($\simeq 50$ Mpc). Analysis of arrival directions of events and study of anisotropies at small and large angular scales may further help to distinguish between different types of sources and to provide constraints on extragalactic magnetic field strength.

Contrary to the astrophysical acceleration scenarios, a substantial fraction of primary photons is expected in the exotic UHECR production models. Hence, sensitive UHECR composition studies are of great importance. These studies, well above the energies available even at the future LHC accelerator facilities, rely on the indirect detection of extensive air showers (EAS) induced by the primary cosmic rays in the atmosphere. Measurements of shower properties in the atmosphere (depth of the maximum of cascade) and at the ground (thickness and curvature of the shower front, muon richness etc.) are confronted with simulations to provide necessary discrimination criteria. An important issue of composition studies is to understand the systematic difference in energy measurement between previous results obtained from the particle density at the ground (AGASA), or from the fluorescence (HiRes) or Cherenkov (Yakutsk) emission in EAS.

The Pierre Auger Observatory was designed (Abraham et al. 2004; The Pierre Auger Project Design Report) to answer these key questions of the UHECR physics. After presenting the Southern Auger site and its current status, we will describe the recent Auger results on the anisotropy studies, and the first estimate of the UHECR spectrum. Two other papers (Roucelle 2006; Billoir & Blanch Bigas 2006) present the results of the studies of photon and neutrino contents in the UHECR.

2 Pierre Auger Observatory

The Southern Auger site is located near Malargüe, in the Mendoza region of Argentina. Its hybrid design allows the simultaneous detection of the same cosmic ray events by two complementary techniques. After

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its completion, the Auger Surface Detector (SD) will consist of 1600 12-tons water Cherenkov tanks spaced in 1.5 km triangular array on the 3000 km^2 area. Three photomuliplier tubes (PMTs) in each tank collect the Cherenkov light from the passage of the electromagnetic and muonic components of showers through the purified water. The PMTs signals are digitized at 40 MHz sampling frequency, which provides a temporal resolution of 8 ns. Signal timing information and the integrated charge values are used for reconstruction of shower geometry (arrival direction and core position). Then an energy estimate can be obtained by comparing the lateral distribution of signal with simulations.

The Auger Fluorescence Detector (FD), once completed, will be composed of 4 fluorescence sites located on the edges of the surface array, with 6 Schmidt design telescopes per site, covering each a 30° range in azimuth and $1° - 31°$ range in elevation. Each telescope consists of 11 m^2 segmented spherical mirrors (radius of curvature 3.4 m), focusing the light from the 2.2 m diameter diaphragm onto a camera of 20×22 PMTs. The image of a shower developing in the field of view of a telescope represents a track of triggered PMTs, which enables to reconstruct a shower-detector plane with a high precision ($\simeq 0.3°$). When, in addition to an FD telescope, one or more SD tanks participate in the event (hybrid detection), the SD timing information improves considerably the shower geometry reconstruction. Then, with the help of the absolute calibration of camera pixels and the knowledge of shower geometry, one can estimate the primary energy from the total amount of fluorescence light. This estimate is nearly calorimetric as it is related directly to ionization loss by electrons and positrons in the showers, and only a small correction ($\simeq$ 10% at Auger energies) should take into account the "missing" energy due to muons and neutrinos. An even more valuable information concerning energy determination is obtained from the so-called "Golden" hybrid events, when the same event can be reconstructed independently by the SD and the FD.

Currently, nearly 1000 ($\simeq$ 60%) SD stations are fully operational, and about 200 more tanks are deployed in the pampa. 18 out of 24 FD telescopes (3 sites) are now completed, and are taking data during clear moonless nights. More details on the Detector performances and calibration, numerous facilities for atmospheric monitoring can be found in the Proceedings of the 29th ICRC at Pune, India (2005) (Auger reports at the 29th ICRC).

3 Anisotropy studies

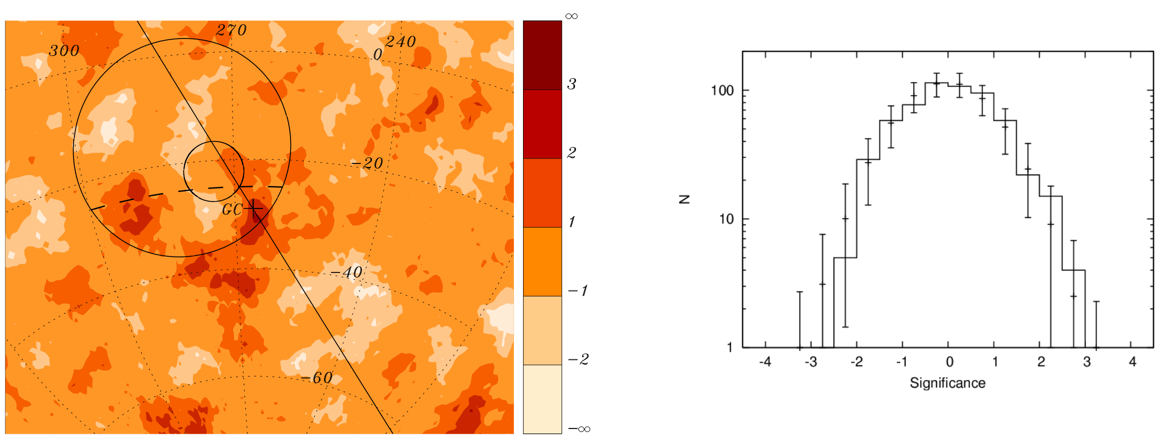

Fig. 1. *(left)* The Auger map of CR overdensity significances near the GC region (top-hat windows of 5° radius). The GC position is marked by a cross on the galactic plane. The large circle represents the AGASA excess region, the dashed line being their field of view limit, and the small circle – the SUGAR excess region. *(right)* The corresponding histogram of overdensities computed on a grid of 3° spacing compared to isotropic expectations (points with 2σ bounds).

The data from 1 January 2004 to 30 March 2006 were analyzed (Auger, in press, [astro-ph/0607382]) to search for anisotropies near the Galactic Center (GC). This region represents an attractive target for such studies, as it harbors the very massive black hole, and the detection of a very close TeV γ-ray source by

H.E.S.S. collaboration (Aharonian et al. 2004) had given birth to a number of theoretical models predicting the flux of neutrons at EeV energies. In addition, recent H.E.S.S. detection of the diffuse γ-ray flux, correlated with the giant molecular clouds near the GC (Aharonian et al. 2006), has also provided the indirect evidence for the cosmic ray acceleration in that region, though at much lower energies. There were previous claims by the AGASA and SUGAR collaborations of significant event excesses at EeV energies near to the GC, for [1–2.5] EeV and [0.8–3.2] EeV energy bands, respectively. The GC passes at $\sim 6°$ from the zenith at the Auger South site latitude, and the Auger dataset for the GC studies (79265 SD and 3439 hybrid events with similar energies $10^{17.9}$ eV $< E < 10^{18.5}$ eV) is significantly larger than that of AGASA or SUGAR.

Figure 1 summarizes the results of our anisotropy analysis for the Galactic Center region. The relative exposure of the different sky directions (coverage map) has been cross-checked using two different techniques leading to a difference of $\sim 0.5\%$ in background estimate, a level well below the Poissonian fluctuations and the excesses to test. Then the significance of eventual anisotropies in the UHECR arrival direction distribution was estimated by comparison of the observed number of events with that expected from an isotropic cosmic ray flux. The significance maps were built in circular windows of 5° radius. This angular scale is convenient to visualize the overdensity distributions in the windows studied by SUGAR (excess size $\sim 5°$) and AGASA (excess size $\sim 20°$). Additional tests have been made with modified energy ranges to take into account possible differences in energy calibration. In all cases, no significant excess has been found in Auger data. We therefore do not confirm the excesses observed by AGASA and SUGAR. In addition, we have set a limit on a point-like source at the GC using the datasets of SD-only and hybrid events (the latter yielding excellent resolution of $\sim 0.6°$).

A scan for correlations of cosmic ray arrival directions with the galactic plane and super-galactic plane has been made, but with a smaller data set, at energies in the [1-5] EeV range and above 5 EeV, and no significant excess has been found (Auger 2005a). A blind search for overdensities in the cosmic ray flux for the same energy ranges and at two angular scales of 5° and 15° has also given the results consistent with isotropy (Auger 2005b).

4 Measurement of the primary cosmic ray energy spectrum above 3 EeV

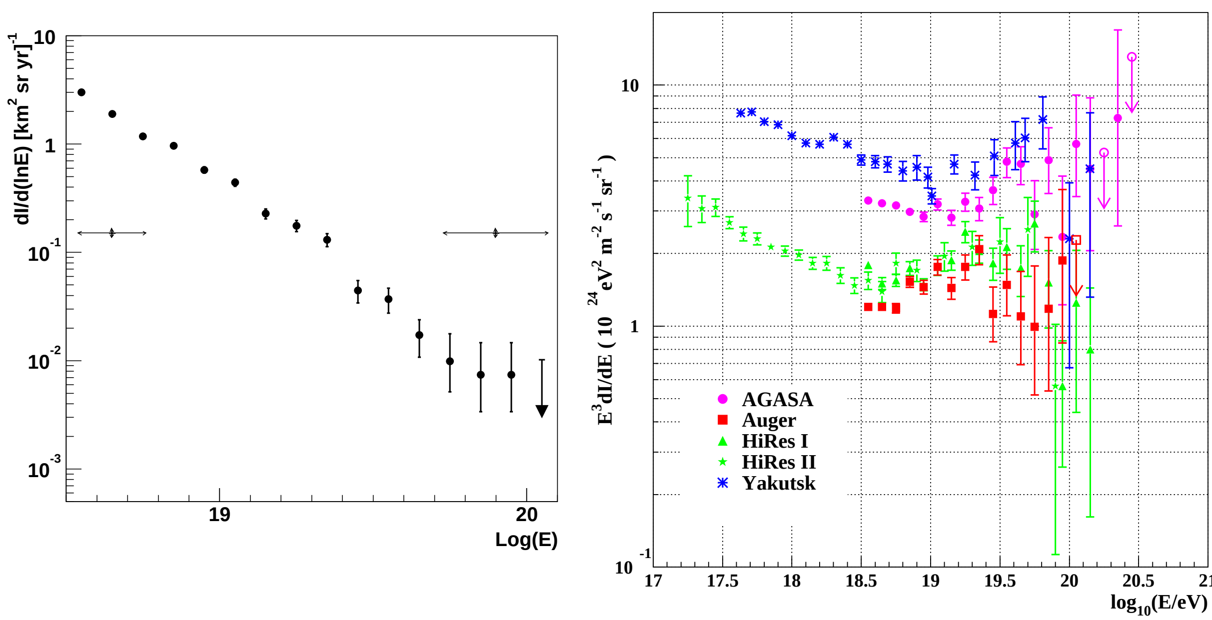

Fig. 2. *(left)* Energy spectrum by Auger (in $E\frac{dI}{dE}$ representation). Errors on data points indicate statistical uncertainty (or 95% CL upper limit). Two error bars indicate the systematic uncertainty at two different energies. *(right)* The measured Auger spectrum (in $E^3\frac{dI}{dE}$ form) is superimposed on the results of the previous experiments (Takeda et al. 2003; Abbasi et al. 2005; Egorova et al. 2004).

The data taken from 1 January 2004 to 5 June 2005 were used to make a first estimate (Auger 2005c) of the primary UHECR spectrum. While the average Auger SD array size for this period was only $\sim 22\%$ of the planned 3000 km^2, the integrated exposure was already similar to those by the largest previous experiments. The method used to derive the spectrum is almost free of any assumptions on primary UHECR composition or hadronic interaction models. It allows to combine the power of large SD array aperture with the nearly calorimetric FD energy measurement.

The energy assignment to the SD events is a two-step procedure. First, we establish for each event an energy-related parameter. We use for this purpose S(1000), the estimate of integrated signal size at a distance of 1000 m from the shower axis, which is determined from a fit of the lateral distribution of signal of all tanks triggered by the shower. Simulations show that S(1000) is almost proportional to primary energy and that at these distances from the axis the fluctuations of lateral distribution are minimal for studied energies and adopted array geometry. The constant intensity cut method, which exploits the nearly isotropy of cosmic rays, is used to rescale S(1000) value from different shower inclinations. At the second step, a rule for converting S(1000) to energy is established using a subset of high quality "Golden" hybrid events.

To derive the spectrum, we used 3525 events above 3 EeV, detected at zenith angles $\theta < 60°$ and falling within the well-defined fiducial area. The simulations (reinforced by an independent check of trigger probability with the hybrid events) show that the array acceptance for such showers is 100%. Consequently, the array exposure for the selected dataset is simply defined by the array geometry and the live-time of SD tanks. The spectrum, obtained by dividing the number of events in energy bins by the exposure value (1750 km^2 sr yr), is shown on the left plot of fig 2.

The large part of indicated systematic errors in energy assignment comes from the limited number of hybrid events that were used to establish the S(1000) – energy conversion, especially at the highest energies. This systematics will of course shrink rapidly with the growing amount of data. Another large sources of systematics from the FD energy scale itself ($\sim 25\%$ in total) are the uncertainty in fluorescence yield (15%) and the absolute calibration of the FD telescopes (12%). Both cited uncertainty values will also be reduced in the near future. However, at this early stage of experiment, one cannot conclude yet on the presence of the GZK cutoff in the spectrum.

The measured spectrum is shown on the right plot of fig 2 with the results of previous experiments. The Auger data points are $\sim 10\%$ below the HiRes flux measures. It should be also noted that preliminary studies based on SD event simulations provide energies that are systematically (by $\sim 25\%$) higher than those derived from the FD calibration. The Pierre Auger Observatory, with its large statistics and the rich information available for each shower, will investigate this intriguing difference.

5 Conclusions

The recent results from the Pierre Auger Observatory, though obtained with the incomplete detector over the first two years of operation out of 20 years planned, have already brought important new insights on the UHECR physics and shown the power of Auger large aperture and hybrid design. There are many advances in the understanding of the detector response. The large panorama of the Auger activities and results can be accessed via the 29th ICRC Proceedings (Auger reports at the 29^{th} ICRC) and the more recent publications.

While the Southern Auger site is still under construction, a preparation work for the Northern site with even larger aperture in Colorado is on-going. At the same time, possible enhancements of the Southern site, that will allow to bring the energy threshold of the detector down to 10^{17} eV and to measure with higher precision the UHECR composition in the region where the transition from galactic to extragalactic component occurs, are discussed. Several options for such enhancements are envisaged, like higher elevation angle FD telescopes, muon counters, and additional surface detectors spaced more closely (in-fill array). There are also planned R & D on shower radio detection. We expect therefore that many of the key questions of the UHECR physics that have been mentioned above will be answered in the near future.

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