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Results from the Pierre Auger Observatory

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The Pierre Auger Observatory is the largest observatory of high-energy cosmic rays. It is located in Argentina and has been taking data since January 2004. Extensive air showers initiated by cosmic rays are measured by the hybrid detector, which combines the sampling of particle density at ground by water-Cherenkov tanks and the measurement of atmospheric fluorescence light by telescopes. New detection techniques, like radio and microwave measurement, are also being tested. Results regarding the energy spectrum, mass composition and arrival directions of cosmic rays are presented here.

Key words: astroparticle physics, cosmic rays

INTRODUCTION

The goal of the Pierre Auger Observatory [10] is the measurement of ultra-high energy cosmic rays (UHECRs), i.e. cosmic rays with energies above 10^{18} eV. The origin and properties of UHECRs are not fully understood yet. These particles have been observed for more than half a century and special attention has been paid to the most energetic ones.

Unlike optical or radio photons, the cosmic rays are charged nuclei and are deflected by magnetic fields during their propagation through interstellar and intergalactic space. Our knowledge of the galactic and extragalactic magnetic fields is limited. Since the deflections caused by the magnetic fields are inversely proportional to the particle energy, we might take advantage of using the most energetic measured cosmic rays for backtracking to a source location.

The investigation of UHECRs is difficult and requires a large effort. First of all, the flux[1] of UHECRs is very low. It falls steeply with energy, decreasing by almost three orders of magnitude per decade of energy. Only one particle per km^2 per year arrives at the Earth above an energy of 10^{18} eV and the flux reduces to less than one particle per km^2 per century at energies above 10^{20} eV. It is clear that a huge detector is necessary for the successful measurement of UHECRs.

Another difficulty in the study of UHECRs is their interaction in the atmosphere. The direct detection of primary particles of cosmic rays is possible only at altitudes higher than $\sim$20 km. Balloon or space borne experiments are too limited in their collection area to measure the low flux of UHECRs and cannot be used. In the 1930s French physicist Pierre Auger [16] found that the primary cosmic ray particle interacts with the atmosphere and many secondary particles are produced in the first and subsequent interactions. Such a cascade of secondary particles is called an extensive air shower (EAS). An extensive air shower develops in the atmosphere while the energies of the secondary particles are sufficient to produce new particles. The number of secondary particles in the shower maximum can be as high as a few billion, but only a small fraction of the secondary particles arrive at ground level.

Two methods have been established for the measurement of EAS. The first one samples the particle density at the ground with an array of detectors measuring in coincidence. The other method is a measurement of ultraviolet (UV) nitrogen fluorescence light emitted along the track of EAS. The properties of the primary cosmic ray particle are reconstructed from the measured data. A detector using both, a surface and a fluorescence detector, is called a hybrid detector. Hybrid detection gives more accurate results in comparison with the results obtained by individual detection techniques.

More details about the measurement and properties of UHECRs can be found in review articles [17, 21] and references therein.

PIERRE AUGER OBSERVATORY

More than 1600 water-Cherenkov surface detectors cover a flat semi-desert area of more than

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[1] The flux is defined as the number of cosmic rays arriving on a unit area from unit solid angle per unit of time.

3000 km^2 near the city of Malargüe, Argentina (69.3° W, 35.3° S, 1400 m a.s.l.) on a triangular grid with 1.5 km spacing. Three large photomultipliers measure Cherenkov photons radiated by relativistic particles passing through purified water in each detector. Each detector is equipped with necessary electronics, battery, solar panel, GPS and radio communication antenna (see Fig. 1).

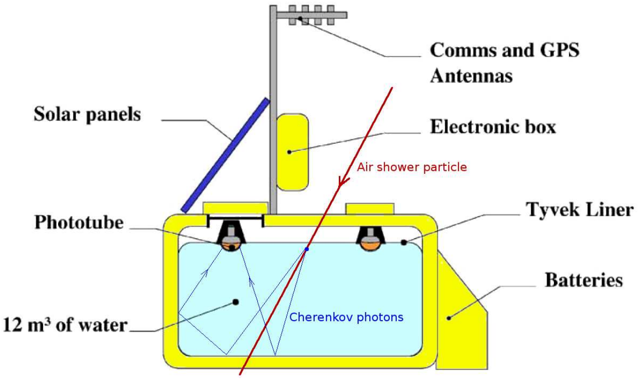

Fig. 1: Water-Cherenkov detector with its components. A secondary particle passing through the detector is indicated together with emitted Cherenkov photons.

The advantages of the surface detector are its autonomous operation, uptime of almost 100% and its well defined aperture [6]. On the other hand the energy reconstruction depends on hadronic interaction models, which can only be validated up to energies available in man-made accelerators. Any usage of hadronic interaction models is necessarily based on theoretical extrapolations from lower to higher energies. However, using the measurements of the fluorescence detector, the absolute energy scale can be estimated almost entirely based on measured data.

The fluorescence detector consists of four sites, each with six fluorescence telescopes, located at the boundary of the surface detector array. The fluorescence telescopes view the atmosphere above the array during clear, almost moonless, nights [7]. The uptime of the fluorescence detector is about 13%. Each fluorescence telescope consists of a spherical segmented mirror, a camera with a matrix of 440 photomultipliers and an aperture with a UV band-pass filter and corrector ring (see Fig. 2).

One of the main advantages of the fluorescence detector is the calorimetric measurement of cosmic ray energies. The charged secondary particles of an extensive air shower excite atmospheric molecular nitrogen, which then emits photons isotropically in the UV range (i.e. into several spectral bands between 300 and 420 nm). Because the emitted intensity is proportional to the energy deposited by the shower along its path, the energy reconstruction is independent of hadronic interaction models, except for only a few percent correction for the invisible component due to muons and neutrinos. Another advantage is the observation of the longitudinal profile, i.e. the number of secondary particles of EAS as a function of atmospheric depth. The position of the shower maximum is sensitive to the type of the primary particle. Therefore the chemical composition of UHECRs can be studied with the fluorescence detector. Knowledge of the chemical composition is crucial for the study of cosmic ray acceleration and propagation.

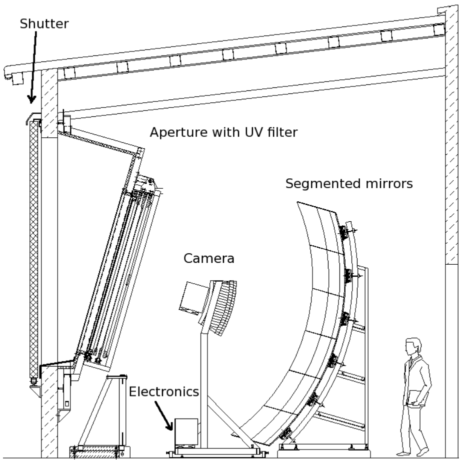

Fig. 2: Drawing of a fluorescence telescope. Light passes through the aperture and is reflected by the mirror to the camera.

Because the fluorescence emission and also light scattering and attenuation depends on the atmospheric conditions between the shower and the telescope, a large array of atmospheric monitors is operated at the Pierre Auger Observatory [5]. The data are also used to prevent cloud-obscured data from distorting estimates of the shower energies, shower maxima, and the detector aperture. Moreover, the sensitivity of the fluorescence detector is regularly monitored using different light sources.

COSMIC RAY ENERGY SPECTRUM

For the calculation of the cosmic ray flux, a knowledge of the detector exposure together with the precise energy reconstruction is necessary. The surface detector has a well defined aperture above energies of 3×10^{18} eV and, moreover, its exposure does not depend on weather conditions. The energy estimator of the surface detector is calibrated by the energy given by the fluorescence detector for a subset of EAS simultaneously detected by both detectors [2, 8, 12]. The correlation between the cosmic ray energy measured by the fluorescence detector and the energy estimator of the surface detector is shown in Fig. 3.

The combined energy spectrum calculated from the surface and hybrid data is shown in Fig. 4. While the fluorescence detector provides data below an energy of 3×10^{18} eV, the surface detector has sufficient statistics even for energies above a few 10^{19} eV because of its higher uptime. Both spectra show agreement for the intermediate energy range.

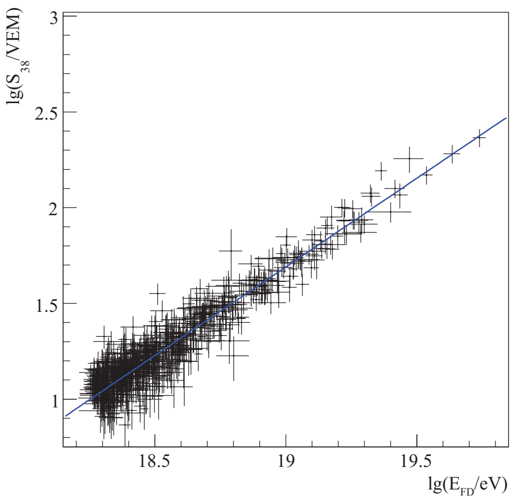

Fig. 3: Correlation between the energy estimator of the surface detector (S_{38}) and the energy measured by the fluorescence detector (E_{FD}).

The flux of UHECRs follows a power law, with two changes of the spectral index. The flattening of the spectrum takes place at an energy of 4×10^{18} eV and this kink is called the ankle. The ankle might indicate the transition from galactic to extragalactic cosmic rays. A similar feature in the cosmic ray spectrum could also result from the propagation of protons from extragalactic sources, placing the transition from galactic to extragalactic cosmic rays at a much lower energy. Various models predict measurable differences not only for the energy spectrum, but also for the chemical composition (see e.g. [17]).

A significant suppression of the flux of UHECRs is observed above 4×10^{19} eV. The suppression is similar to the prediction of the Greisen-Zatsepin-Kuzmin (GZK) mechanism [20, 22], but it could also be related to a change of the injection spectrum in the sources. The GZK mechanism is an interaction of cosmic ray protons above the GZK energy of $\sim 4 \times 10^{19}$ eV with the photons of the cosmic microwave background. The energy loss of the interacting cosmic ray continues until the particle energy falls below the GZK energy. As a result, cosmic rays above the GZK energy cannot travel over distances larger than ~ 100 Mpc without significant energy losses[2]. This mechanism excludes far distant sources from making a significant contribution into the UHECR flux above the GZK energy.

The shape of the cosmic ray spectrum differs for proposed models of the origin of UHECRs. It is affected not only by the properties of the sources but also by propagation processes.

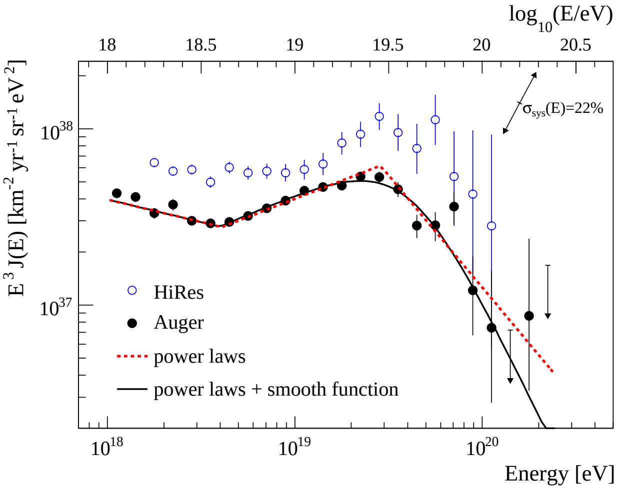

Fig. 4: Scaled energy spectrum derived by the Auger experiment and compared with the data from another detector. The systematic uncertainty of the energy scale of 22% is indicated by arrows.

COSMIC RAY COMPOSITION

The development of an extensive air shower depends on the type of the primary particle. The longitudinal profile measured by the fluorescence telescopes and also the lateral distribution of secondary particles sampled by the surface detector provide information about the properties of the primary particle. It has been found, that the contribution of neutral particles, which could be interesting for finding the UHECRs sources, to the flux of UHECRs is very low. The upper limits on the fluxes of known stable neutral particles, photons [3] and τ-neutrinos [4], are so low, that several exotic models of the origin of UHECRs (e. g. the decay of superheavy particles) have been excluded.

The flux of UHECRs is mainly composed of atomic nuclei. The most precise measurement of the chemical composition is obtained by the observation of the depth of the shower maximum as well as its fluctuations [9]. The EAS produced by lighter primaries (e. g. protons) propagate deeper into the atmosphere than heavier nuclei (e. g. iron nuclei) and show larger fluctuations. The identification of the primary particle is not possible for a single event, because of the random nature of EAS.

The average depth of the shower maximum is found to change with energy as do shower-to-shower fluctuations. Protons or other light nuclei would be preferable for the study of UHECR sources, because they would be less affected by the magnetic fields

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[2] Ultra-high energy nuclei lose energy in photodisintegration on all photon fields.

during their propagation from the sources. Unfortunately, the results of both methods suggest heavier composition at the highest studied energies (see Fig. 5). It is worth mentioning, that the composition above the energy of 4×10^{19} eV is not clear yet because of a lack of statistics.

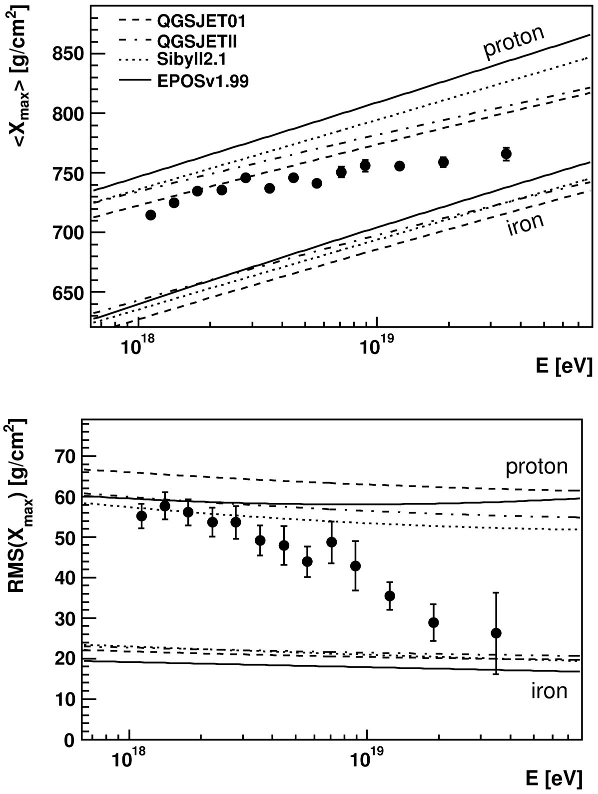

Fig. 5: Average depth of shower maximum (top) and shower-to-shower fluctuations (bottom) as a function of energy together with air shower simulations using different hadronic interaction models.

COSMIC RAY ARRIVAL DIRECTIONS

The uncertainty of reconstructed arrival directions of UHECR by the Pierre Auger Observatory is less than 1.5° for events triggering 4 surface detector stations and better than 1.0° for events with six and more stations (i.e. for higher energies). The deflection of cosmic rays propagating in known magnetic fields is comparable with the angular resolution of the detector even for protons at the highest energies. The deflection is more than one order of magnitude higher for iron nuclei.

As mentioned above, the sources of UHECRs above energies of 4×10^{19} eV must lie closer than $\sim$ 100 Mpc. The number of possible astronomical sources (candidate sites are active galactic nuclei (AGN), radiogalaxies, clusters of galaxies, etc.) within the GZK horizon is limited. These close-by objects are clustered and we might expect anisotropic arrivals of UHECRs even for a mixed hadronic composition.

An anisotropy has been observed by the Pierre Auger Observatory for events above $\sim 5.5 \times 10^{19}$ eV. The sky positions of measured arrival directions are preferably closer than $\sim$ 3° from the positions of AGN with distances less than 75 Mpc [1]. The latest results show that the fraction of the highest energetic cosmic rays correlating with nearby AGN directions is 38%, while 21% is expected for isotropic flux, see Fig. 6. The list of events has been published in [13]. The largest excess has been measured around the position of our closest radiogalaxy Centaurus A.

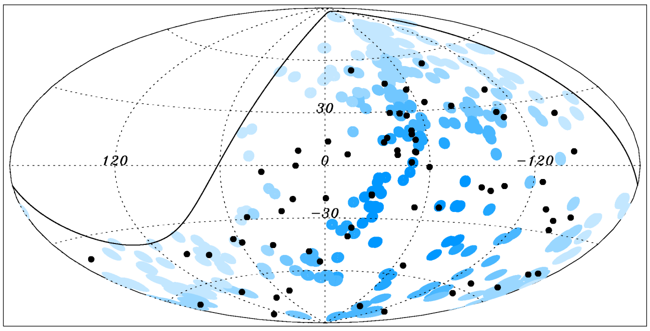

Fig. 6: The arrival directions of 69 events measured by the Pierre Auger Observatory above 5.5×10^{19} eV (small dark dots) together with the positions of nearby AGN (dimmer areas, where darker shade indicates larger relative exposure). Galactic coordinates are used in the map.

No other excess has been found in the data collected by the Pierre Auger Observatory. The direction towards the Galactic Centre shows no excess of arrival directions [11], nor is there any positive signal found in large-scale anisotropy studies [14]. The upper limit for the latter result is shown in Fig. 7.

ENHANCEMENTS OF THE OBSERVATORY

The study of cosmic rays with energies between 10^{17} and 5×10^{18} eV are of special interest. The transition from a galactic to an extragalactic flux might occur in this energy range. A discrimination between astrophysical models requires a precise measurement of the spectrum as well as the chemical composition. Two extensions have been built in the Auger experiment. High Elevation Auger Telescopes (HEAT) are three fluorescence telescopes which can be tilted 45° above the horizon. They extend the lower energy threshold to well below 10^{17} eV. A shower measured by a HEAT telescope and one standard fluorescence telescope is shown in Fig. 8. This is a low energy shower which could be reconstructed due to the additional measurement at higher elevation. There is also an extension of the surface detector close to the HEAT site which is going to be combined with underground muon counters. This infill array lowers the energy threshold of the surface detector down to $\sim 5 \times 10^{17}$ eV.

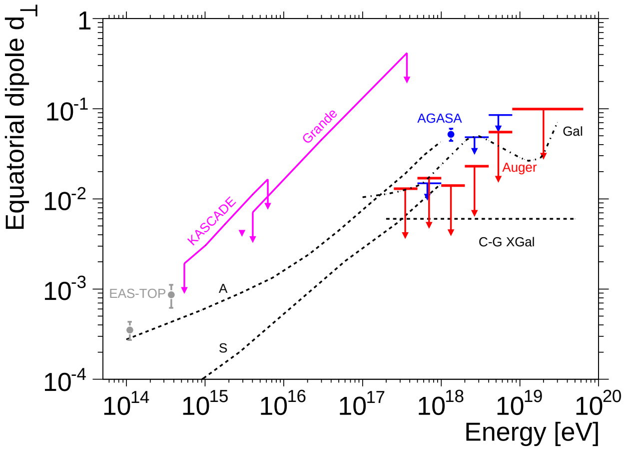

Fig. 7: Upper limits on a dipolar-type anisotropy given by different experiments compared with calculated predictions (for more detail see [14]).

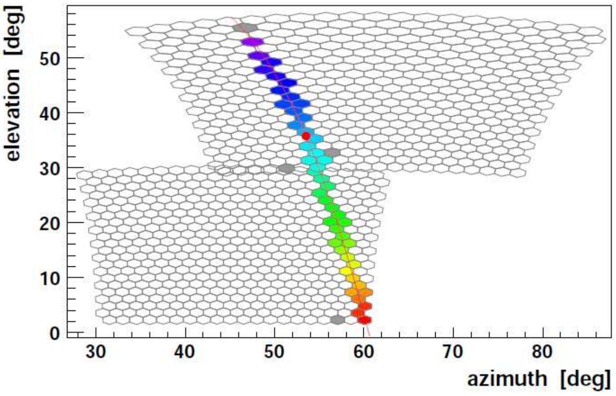

Fig. 8: Trace of a low energetic event measured by two cameras. The upper one belongs to the elevated HEAT telescope, the lower one is a standard fluorescence telescope. Colours indicate the time evolution of the measured signal.

Other activities are connected with the radio detection of EAS. Radio detection might play an important role in the future, because a low-cost radio detector could have 100% uptime and sensitivity to the chemical composition. Radio emission from EAS in the frequency range of 30–80 MHz is detected by a prototype radio telescope array (AERA – Auger Engineering Radio Array) [18]. A simulated radio signal is shown in Fig. 9. Predicted microwave emission [19] is going to be investigated by parabolic antennas equipped with a matrix of receivers measuring in C band (3.4–4.2 GHz) and Ku band (10.95–14.50 GHz).

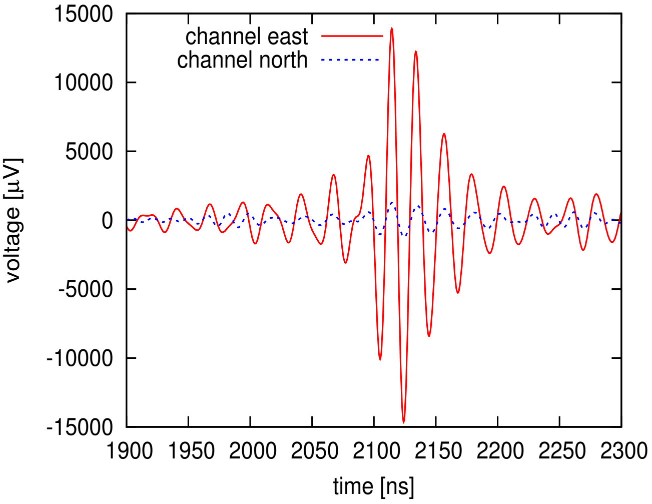

Fig. 9: Time traces of a simulated radio signal in two channels of the AERA detector [15].

CONCLUSIONS

The Pierre Auger Observatory and its results have been described. The observatory provides valuable data for the study of ultra-high energy cosmic rays. Major achievements of the observatory are the precise measurement of the cosmic ray flux and chemical composition, as well as the detailed study of arrival directions. In addition, the observatory has become the basis for testing several new detection methods.

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