Observations of ultra high energy cosmic rays

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Abstract. The Auger Observatory was designed to study the highest-energy cosmic rays by measuring the properties of the showers produced in the atmosphere. The most important results are the observation of the suppression of the high-energy events due to the GZK effect and the discovery of the angular correlation with nearby extragalactic objects.

1. The Auger Observatory

The Auger Observatory, located in the province of Mendoza (Argentina) at the latitude of about 35° S and altitude of 1400 m above see level, is a hybrid system, a combination of a large surface array and a fluorescence detector [1].

The surface detector (SD) is a large array of more than 1600 water Cherenkov detectors spaced at a distance of 1.5 km and covering a total area of 3000 km². Each detector is a plastic tank filled with purified water [2]. The tanks activated by a cosmic ray shower record the particle density and the time of arrival. This information is used to derive the direction of the axis of the shower and the point of impact at ground. An example of an event of high energy as observed by the SD is shown in Fig. 1. The signal S of each water Cherenkov detector is expressed in units of Vertical Equivalent Muons (VEM) which represents the signal produced by a muon traversing the tank vertically.

![Figure 1](image-url)  
Figure 1. Example of an event of high energy as observed by the SD. As shown in the left panel the shower has activated 13 water Cherenkov detectors distributed over an area of about 20 km². The area of the circles is proportional to the logarithm of the observed signals which are plotted in the right panel as a function of the distance from the reconstructed shower axis. The signals expressed in units of VEM are shown together with the results of the LDF fit.
The dependence of $S$ on the distance $r$ to the axis of the shower is described with a simple analytical expression known as Lateral Distribution Function (LDF) which is fitted to the data. The fit provides a value of the signal which would be observed at the distance of 1000 m from the shower axis. This interpolated quantity, $S(1000)$, is a good energy estimator in the sense that it is well correlated with the energy of the primary.

The fluorescence detector (FD) of the Auger Observatory consists of 24 telescopes located in four stations which are built on small elevations on the perimeter of the site. The telescopes measure the longitudinal development of the showers by observing the fluorescence light produced by the interaction of the charged particles of the showers with the nitrogen molecules of the atmosphere. The field of view of each telescope is $30^\circ \times 30^\circ$. The FD may operate only in clear moonless nights and therefore with an uptime of only about 13%. The method relies on the knowledge of the fluorescence yield and its dependence on pressure and temperature [3].

The absolute calibration of the FD telescopes is done using calibrated light sources. The attenuation of the fluorescence light due to Rayleigh and aerosol scattering along the path from the shower to the telescopes is continuously monitored.

The energy deposited by the shower particles as a function of the depth is obtained from the observed light profile. Examples of longitudinal profiles of showers are shown in Fig. 2 together with fits using the Gaisser-Hillas analytical expression.

![Figure 2](image)

Figure 2. Examples of measured longitudinal profiles of high-energy showers. The energy deposited by the particles of the shower is plotted as a function of the atmospheric slant depth together with fits using the Gaisser-Hillas form.

Left panel: energy $\approx 1.5 \times 10^{19}$ eV, zenith angle $\approx 55^\circ$. Right panel: energy $\approx 4.5 \times 10^{19}$ eV, zenith angle $\approx 36^\circ$.

2. The Energy Calibration.

The method used by the Auger collaboration to measure the energy spectrum exploits the hybrid nature of the Observatory using the data itself rather than simulations [4]. For each event, the energy estimator $S(1000)$ is obtained from the LDF fit. The estimator $S(1000)$ depends on the zenith angle because the effective atmospheric thickness seen by the showers before reaching ground changes with the zenith angle. The value of $S(1000)$ corresponding to the median zenith angle of $38^\circ$ is used as a reference and the zenith angle dependence of the energy estimator is determined assuming that the arrival directions are distributed isotropically. The estimator $S_{38}$ is corrected for the missing energy (neutrinos and muons) using the mean value between proton and iron as derived from simulations of the showers. At the energy of $10^{19}$ eV the correction is 10% (about 8% for protons and 12% for iron nuclei). A sample of good quality hybrid events was selected to establish the correlation between the fluorescence detector energy $E_{FD}$ and the energy estimator $S_{38}$ as shown in Fig. 3.
Figure 3. The calibration of the energy estimator $S_{38}$ using the calorimetric energy from the FD is shown in the left panel together with the result of the fit. The right panel shows the energy resolution (17%).

The absolute energy calibration of $S_{38}$ as obtained from the fit represented by the line in the left panel of Fig. 3 is then used for the full set of events with higher statistics which is measured by the SD only.

The Auger method for the absolute calibration of the showers energy is at present affected by a systematic error of about ±20%, mainly due to the uncertainty on the reconstruction of the shower profile, on the calibration of the FD telescopes and on the fluorescence yield.

3. The Energy Spectrum.
The data presented here refer to showers with zenith angle below 60° because the analysis of more inclined showers requires a more complex and sophisticated treatment. Two different methods were used to measure the energy spectrum
- SD events with energy calibration as explained in Sec 2. ($E > 3 \times 10^{18}$ eV).
- Hybrid events with at least one surface detector activated ($E > 10^{18}$ eV).

Hybrid events enable lower energies to be reached. The two sets of data have the same energy calibration and therefore can be combined together. The resulting spectrum [5] is shown in Fig. 4.

Figure 4. The combined energy spectrum from the Auger Observatory. The total number of events is about 37,000. The red line drawn through the data in the central region is only meant to give a qualitative indication of the two features (the ankle and the GZK suppression).
A simple way of describing the energy dependence of the spectrum in the three regions separated by the two breaking points is provided by a fit with three power law $E^\gamma$ which is done leaving as free parameters also the two values of the energy where the spectral index $\gamma$ changes (see Fig. 5).

![Fig. 5](image1.png)

Figure 5. The Auger data are presented as Flux $\times E^3$ together with the fit described in the text. The results of the fit are also shown. The ankle and the GZK suppression are clearly seen.

The Auger spectrum is shown again in Fig. 6 together with the HiRes data. The disagreement between the two experiments seems to be due to different energy scale. A relative shift of the energy scale by an amount close to the quoted systematic error would bring the two sets of data in agreement.

![Fig. 6](image2.png)

Figure 6. The Auger data are presented as Flux $\times E^3$ together with the three power law fit (red dots) and a fit with smoothing in the GZK region (black line). The systematic error on the Auger energy scale is indicated. The HiRes data are also shown.
4. Correlation with nearby galaxies.

The observation of the GZK cutoff implies that the events close to the high-energy limit of the spectrum are of extragalactic origin. The Auger collaboration has been trying to identify the actual sources of these very high energy particles. A first attempt comparing the observed directions of cosmic rays with energy above 55 EeV with the position on the sky of the AGN galaxies listed in the Véron Cetty & Véron (VCV) catalogue at distances less than 75 Mpc was published in 2008 [6]. Table 1 updates that early study. The correlation increases significantly when the data around the galactic plane, where the catalogue is incomplete, are discarded. The probability that a “a priori” isotropic distribution would, by chance, simulate the observed distribution is at the level of a per cent.

| January 2004 - March 2009 | Number of events E > 55 EeV | Correlated with AGN \( \psi = 3.1 \) degree | Expected for isotropy |
|---------------------------|----------------------------|----------------------------------|-----------------|
| Excluding band on the galactic plane (|b| > 12 degree) | 45 | 25 | 11.3 |

Table 1. Results of the study of correlation of the high-energy Auger events with respect to the AGN galaxies listed in the VCV catalogue.

The distribution of the angular separation between the 58 events with E > 55 EeV and the closest AGN within 75 Mpc is shown in Fig. 7.

Figure 7. The distribution of the 58 events with E > 55 EeV and the closest AGN within 75 Mpc.

These results provide a strong hint for the identification of the sources of very high energy cosmic rays as special galaxies of the AGN type.

The values of the parameters which were determined empirically as providing the best correlation with catalogues of galaxies are consistent with simple expectations. In fact the events with energy above 55 EeV are at the limit of the energy spectrum in the region of the GZK suppression which operates on extragalactic particles. In Fig. 8 the radius of the GZK sphere for protons is shown as a function of their observed energy on Earth for different fractions of the total number of events. The radius of the GZK sphere shrinks as the energy increases. For E > 55 EeV one expects that more than 40% of the events would come from distances less than 75 Mpc. This is consistent with the correlation results.
On the other hand, as shown in Fig. 9, the expected deflection in the galactic magnetic field of protons with energy of 60 EeV is around 3° and therefore a correlation angle of 3.1° appears plausible. Therefore the overall picture, GZK suppression and correlation with AGN galaxies appears consistent.

Figure 8. Calculation of the radius of the GZK sphere as a function of the observed energy of protons on Earth. The lines indicate the fraction of events which is actually observed for a given energy and a given distance of the source.

Figure 9. The calculated deflection of protons of 60 EeV in the galactic magnetic field [6].

References
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