2.6 Cosmic Rays
Pierre Auger Observatory

Management: prof. dr. S.J. de Jong (PL)

Ultra-high-energy cosmic rays are the most energetic particles we know, exceeding the LHC energy by many orders of magnitude. Yet we do not know the physics that is needed to generate them in the heavenly bodies, nor do we know the physics that governs their interactions with our own atmosphere. The Pierre Auger Observatory is world's largest cosmic ray observatory located on 3,000 km² near Malargüe in the province of Mendoza in Argentina and was built to resolve these mysteries.

A consortium of Dutch groups from Nikhef, the University of Groningen and the Radboud University Nijmegen has been participating in the Pierre Auger Collaboration since 2005. Besides analysing the Auger surface and fluorescence detector data, the Dutch group pioneers a complementary technique to measure ultra-high-energy cosmic rays by detecting the radio frequency radiation emitted by the air shower.

The origin of ultra-high-energy cosmic rays

The Pierre Auger Collaboration had shown definitively that the energy spectrum of cosmic rays exhibits a sharp drop around 10^{20} eV. This drop is compatible with the Greisen-Zatsepin-Kuz'min (GZK) cut-off caused by the universe becoming opaque due to resonant collisions between ultra-high-energy protons and the photons of the cosmic microwave 2.7 K background radiation. Past measurements by the Pierre Auger Collaboration already have cast some doubt on this explanation, and this year's results further established that the GZK cut-off cannot be the entire story and even the extent of its contribution to the cut-off remains unclear.

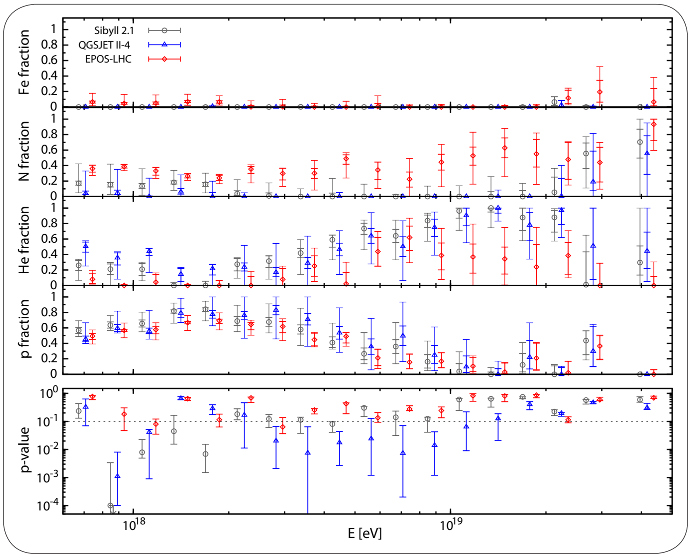

Figure 1. Fitted fraction of protons, helium, nitrogen and iron nuclei as a function of energy of the cosmic rays. The lower panel gives the fit probability for each fit. Different theoretical models, Sibyll2.1, QGSJET II-4 and EPOS-LHC, are used for the fit function.

Detailed composition spectra in the energy range $10^{18.5}$–$10^{19.5}$ eV show that most cosmic rays at these energies probably have a mass somewhere between the extremes of that of a proton or iron nucleus (see Fig. 1).

These spectra are measured with the fluorescence detector, one of the main hybrid detection methods of the Pierre Auger Observatory, which registers the fluorescence light that is caused by the particle shower in the atmosphere. This detector can only operate in darkness, which is about 13% of the time. The other main detection method is the surface detector that consists of 1.5 km spaced water Cherenkov tanks particle detectors that operate 24/7. This surface detector was not built with the intention to measure cosmic ray composition, but recently analyses have been developed that show that a composition measurement is possible with about half the resolution of the fluorescence detector, but on ten times as many events.

The weak anisotropy signal that remains in the Auger data is commensurate with cosmic ray masses, and therefore electric charges that are so large that accurate pointing to even relatively nearby sources is excluded. If the arriving cosmic rays are electrically neutral, they should be pointing to their sources quite accurately. However, both a dedicated analysis that required cosmic ray showers to be compatible with incoming photons, as well as an interpretation of incoming cosmic rays as neutrons have not revealed any point sources. Ultra-high-energy cosmic rays: we know they are there, but we have no idea yet where they are coming from.

Particle interactions at ultra-high energy

Collisions of ultra-high-energy cosmic rays on atmospheric molecules provide hadronic interactions at an energy that exceeds the LHC centre-of-mass energy by one to two orders of magnitude. Although progress was made in incorporating LHC results, some mysteries were not solved. The number of muons in Monte Carlo simulations is very significantly smaller than the number measured in experimental data. Also the depth at which most muons are produced that reach the Earth's surface cannot be described by Monte Carlo simulation for any reasonable composition mix of cosmic rays. Muons in ultra-high-energy hadron collisions: A sign of new physics?

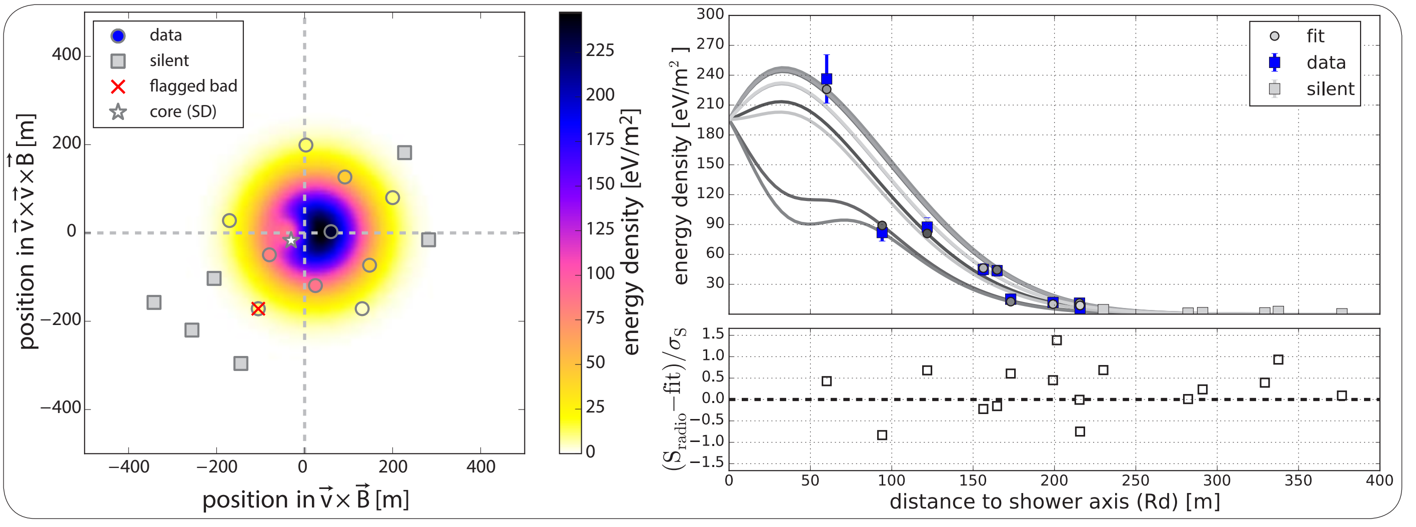

Figure 2. Lateral signal distribution of a single cosmic ray event in the plane perpendicular to the shower axis. Left: The energy density in the shower plane. The measurements are indicated as circles where the color shows the energy density. Grey squares are stations with signal below threshold and the red cross marks a rejected station. The background map shows the parametrisation of the lateral distribution function (LDF). Right: The radio energy density versus the distance to the shower axis. Blue squares are the measurements whereas the circular symbols indicate the value of the LDF parametrisation at the position of the measurement. Gray curves show the radial falloff along a line connecting the radio core position with every station position. Also shown are the residuals in units of the individual uncertainty of the measurement.

Upgrade of the Pierre Auger Observatory

To allow an event-by-event determination of the composition of ultra-high-energy cosmic rays an upgrade is being planned for the Pierre Auger Observatory. The main upgrade component, the dedicated detection of muons in the extensive air showers, has been agreed on as an additional detection layer on top of all water Cherenkov surface detector tanks. This addition is aimed at a separation of the muon and electromagnetic component of the shower for each measurement station and will allow to determine the cosmic ray composition event-by-event. Subsequently selecting the ultra-high-energy protons, guarantees that they have an energy at which they are hardly bent by the cosmic magnetic fields and thus point back to their sources. To enhance the capabilities of the surface detector, especially for composition measurements, it will be equipped with upgraded electronics with a larger sampling rate and a larger dynamic range. The fluorescence detector will be operated allowing for a larger background, thereby extending the time it can operate by about a factor of two.

The collaboration is currently investigating the realisation of a complementary array that provides an area in Auger of about 100–300 km^2 with a dense set-up of conventional detectors, as well as with dedicated muon detectors that are covered with a few meters of soil as a muon filter. This complementary array will both calibrate the main upgrade as well as measure in detail the composition of cosmic rays in the energy range of 10^{17}–10^{18} eV, where the transition from galactic to extra-galactic sources is thought to occur.

Radio detection of cosmic rays

The co-operation on radio detection of cosmic rays between the LOFAR radio telescope and the Auger Engineering Radio Array (AERA) has proven extremely fruitful. A detailed description of the spatial distribution of the radio signal can now be predicted and fitted to the experimental data. In Fig. 2 an example of an event is shown with a fitted lateral energy density profile. The non-rotational invariance around the shower axis can easily be noted and is due to the interference from geomagnetic radio wave emission and the negative charge excess that develops in the shower front. The maximum in the lateral density profile away from the shower core is due to the forming of the Cherenkov beam that results from the diffractive index of the atmosphere. These fits provide an accurate energy estimate for the cosmic rays and determine the composition on an event-by-event basis with an accuracy that is unprecedented. The use of polarisation information promises to further improve our understanding of the radio signal and to even better measure the cosmic ray properties. The AERA will undergo a modest extension in 2015. The next step is to prepare for a larger array that can match the Auger complementary array upgrade.