THE PIERRE AUGER OBSERVATORY: COSMIC ACCELERATORS AND THE MOST ENERGETIC PARTICLES IN THE UNIVERSE

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Abstract

Cosmic ray particles of more than 100 EeV energy have been observed, a hundred million times more than we can produce in accelerators. What are the origin and nature of these particles? How do they propagate to Earth? Do they offer a new kind of astronomy? What can we learn about their interactions in the atmosphere? The talk presents the Pierre Auger Observatory, an international project dedicated to understand the most energetic particles in the Universe.

INTRODUCTION

Cosmic rays are energetic particles from space that continuously hit the Earths atmosphere, e.g. protons, heavier nuclei, photons and neutrinos. After Victor Hess' heroic discovery balloon flights in 1912, extensive air showers were recorded and recognized by Pierre Auger in 1938 usingn one of the first ground detector arrays. A steepening of the power-law energy spectrum around 10^{15} eV was found by Kulikov and Khristiansen in 1958, the so-called knee. It took until 2002 when the KASCADE group demonstrated that the knee was caused by a decrease of the flux of *light* particles only. John Linsley reported the first event with energy greater than 100 EeV in 1963. Soon afterwards Greisen, Zatsepin and Kuzmin predicted that the cosmic microwave background photons would strongly limit the propagation protons above a threshold energy of 60 EeV. This is the so-called GZK effect. A flattening of the spectrum, the ankle, was established in the early 1990s by pioneering measurements using the Volcano Ranch, SUGAR, Haverah Park, Yakutsk, AGASA, Fly's Eye and HiRes instruments. They also reported highly interesting – and somewhat controversial – flux measurements above the GZK threshold energy. A major review [1] gives a detailed account of these foundations of cosmic ray research. New facilities have been conceived to resolve these issues, including the Pierre Auger Observatory that is the subject of this presentation.

GALACTIC AND EXTRAGALACTIC COSMIC RAYS

The energies of cosmic rays extend from less than a GeV to more than 10^{20} eV. The energy spectrum follows a power law $dN/dE \propto E^{-\gamma}$ over a wide energy range. The spectral index γ is ≈ 2.7 at energies up to several PeV. Then a steepening is observed, the so called *knee*, with $\gamma \approx 3.1$ up to 1 EeV ($\equiv 10^{18}$ eV). At about 4 EeV the spectrum flattens again: the *ankle*. Finally, above 50 EeV a flux suppression is observed that is compatible with the GZK effect. Figure 1 shows a compilation of measurements; the flux has been multiplied with a suitable power of the particle energy ($E^{2.5}$) to better visualize the spectral features mentioned above (see [2] for references and further details).

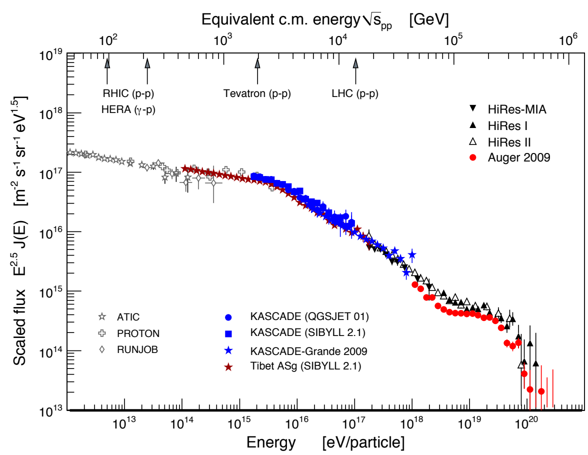

Figure 1: All-particle cosmic-ray energy spectrum.

The equivalent energy in the center-of-mass system is also displayed at the top of Figure 1: only now with the LHC the energy reach is extended beyond the knee. However, the flux is falling steeply with energy so that direct measurements with balloons or satellites are limited to energies below the knee: the intensity of cosmic rays decreases from about 1000 particles per square meter and second at GeV energies to about one particle per square meter and year at a PeV to less than one particle per square kilometer and century at the highest energies. Unlike in accelerator studies, the composition of the "cosmic beam" is not well known. Individual primary particles can be resolved with balloon-borne and space-borne detectors up to TeV energies. At energies exceeding 100 TeV the flux is so low that indirect measurements must exploit the extensive air showers, cascades of millions or billions of secondary particles.

The charged cosmic-ray particles are deflected many times in the magnetic field of our galaxy (typically 3μG) so that their arrival directions become completely isotropic unless at the highest energies. Spallation processes in the interstellar medium affect the abundance of radioactive nuclei, from which a residence time in the galaxy of about 15 million years is deduced, as well as an effective galaxy size of a few kpc, much larger than the galactic disk height. The energy density of cosmic rays is about 1 eV/cm^3, comparable to the values for visible star light, the galactic magnetic fields and the microwave background.

Following first ideas by Enrico Fermi in 1948 a kind of a standard model of cosmic-ray acceleration has been developed: charged particles are trapped in regions with magnetized plasma shock waves, in which they repeatedly gain an amount of energy $\Delta E \propto E$ when they pass through the shock regions. The probability to escape from the region increases with energy; in this way a power-law energy spectrum is obtained naturally. The spectral index is further influenced by global energy-dependent leakage of particles from the galaxy.

Supernova remnants (SNR) have been prime candidates to be the cosmic acceleration sites: three supernova explosions per century could sustain the observed energy density assuming that 10% of their kinetic energy is transformed into particle acceleration. Using typical values of Type II supernovae exploding in an average interstellar medium yields $E_{\max} \approx Z \cdot 10^{14}$ eV and up to one order of magnitude larger for some types of supernovae, where Z is the particle charge. It has also been suggested that the cosmic rays themselves interact with the magnetic fields in the acceleration region, leading to an amplification of the fields, which in turn results in much higher maximum energies. With this mechanism cosmic rays are supposedly accelerated up to 10^{17} eV (0.1 EeV).

Conceptually, the magnetic field strength B in the source region and its size R are related to the maximum acceleration energy by $E_{\max} \simeq 1 \text{ EeV } Z\, \beta\, (R/\text{kpc})\, (B/\mu\text{G})$, where β is the shock velocity in units of c. A graphical representation of this *Hillas equation* is shown in Figure 2.

The knee is interpreted as the upper limit of acceleration by galactic supernovae, while the ankle is associated with the onset of an extra-galactic population that is less intense but has a harder spectrum that dominates at the highest energies. As cosmic rays of energy greater than 10 EeV are no longer confined by galactic magnetic fields, it is natural to assume that they are produced by extra-galactic sources. However, such energies are difficult to reach. In addition to the Hillas equation there are more conditions, e.g. from synchrotron losses in too strong magnetic fields or nuclear interactions in too dense environments, that further restrict the list of the few viable candidate sources for such energies: active galactic nuclei (AGN), radio lobes of FR II galaxies, and gamma-ray bursts. After decades of efforts to model the mechanism for a "cosmic 100 EeV accelerator" we still have no blueprint.

In alternative, non-acceleration scenarios ultra-high energy cosmic rays are produced in decays of super-heavy objects such as super-heavy dark matter or topological defects. All of these models postulate new particle physics

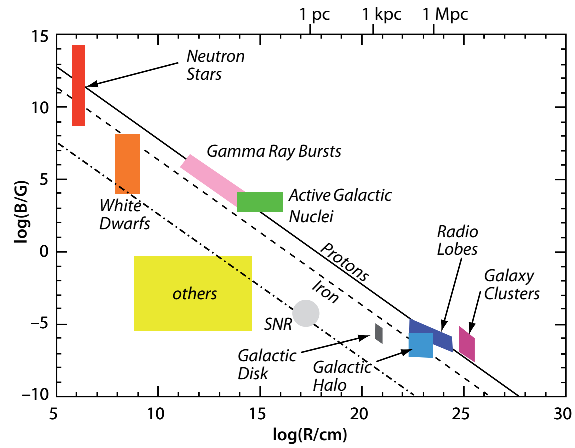

Figure 2: Astrophysical objects are classified by their size R and magnetic field B. The Hillas equation corresponds to straight lines representing certain maximum energies (solid line: 100 EeV protons, dashed line: 100 EeV iron nuclei, dash-dotted line: 100 TeV protons; $\beta = 1$).

and predict typically high gamma-ray fluxes at ultra-high energy. They are now disfavored except for the highest energies due to already stringent limits on the flux of photons.

The energy spectrum presents highly convoluted information about the sources, the particles themselves and their propagation to Earth. Independent inferences about the nature of the cosmic particles are desperately needed. While the original GZK effect had been conceived for protons, the scattering of heavier nuclei in the various background radiation fields has been studied recently. The result is that nuclei of intermediate mass are quickly photo-desintegrated, while protons and iron may survive. For 60 EeV primaries, 50% of the protons are from within a 100 Mpc sphere, while the corresponding distance is 80 Mpc for iron and only 20 Mpc for CNO-like nuclei.

A coherent description of the particle physics and astrophysics of the extremely rich phenomena of cosmic rays is emerging - however, it is still incomplete and many important questions cannot be answered yet: Where do they come from? What kind of particles are they? How can they be accelerated to such high energies? What can we learn about cosmic objects, large-scale structure and magnetic fields? What can we learn about particle interactions at 300 TeV in the center-of-mass system?

THE PIERRE AUGER OBSERVATORY

The Pierre Auger Collaboration comprises almost 500 scientists in 18 countries. The southern site in Mendoza, Argentina, consists of 1,660 water-Cherenkov detectors spread over 3,000 km^2 on a triangular grid with 1,500 m spacing. This surface detector array (SD) is overlooked by four fluorescence detectors (FD), which are arranged at the perimeter of the SD; they consist of 6 individual telescopes each. The FD yields a calorimetric optical shower

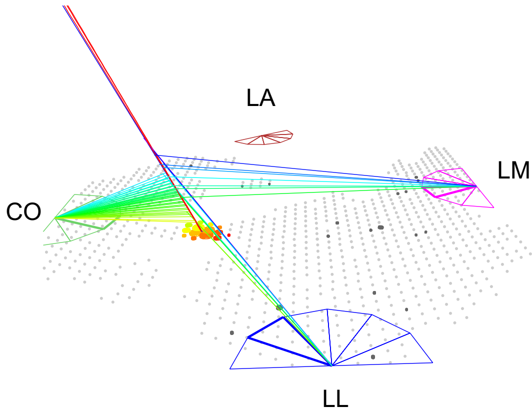

Figure 3: Example of a hybrid event with multiple optical observations. Each dot represents a SD station. The labels represent the four fluorescence detector stations Loma Amarilla, Los Morados, Los Leones and Coihueco. The fields of view are also indicated. The event is color-coded in terms of signal arrival time.

detection and can be calibrated with very little dependence on shower models. The details of the longitudinal shower development, in particular the depth of the shower maximum, X_{max}, are directly observable on about 10% of the events. Figure 3 shows an example of such a fourfold hybrid shower measurement.

Auger South has been collecting physics data since January 2004. The properties and performance of the Auger instruments have been published in [3]. The operation of Auger South, the performance of the detector systems and the instrumental enhancements for the future, including Auger North, are described in [4]. A public internet display of 1% of the events recorded by the Auger Observatory is available online at http://augersw1.physics.utah.edu/ED/.

The Southern Auger Instrument

Each SD station is a 3.6 m diameter polyethylene tank containing a sealed liner with a reflective inner surface. The liner contains 12,000 l of pure water. Cherenkov light produced by the passage of particles through the water is collected by three nine-inch-diameter photomultiplier tubes. The signals are digitized at 40 Ms/s. The stations are autonomously operating with a solar power system, a battery and local electronics. A vertically arriving cosmic ray shower of 10 EeV typically triggers 8 detectors. For most analyses we use showers up to 60° zenith angle, which yields a nominal aperture of 7,000 km^2 sr. Eventually, showers with larger zenith angles will be reconstructed routinely and added to the data set. The SD has full acceptance above 3 EeV, and nearly constant exposure as function of the zenith angle. The effective area of the entire array at any time can be calculated from low-level trigger data sent by each detector every second. The integrated exposure is currently 14,000 km^2 sr yr and is known to 3%.

Each individual telescope of the FD images a portion of the sky of 30° in azimuth and in elevation. Light is collected by a segmented spherical mirror of 3.6 x 3.6 m^2 through a UV-transparent filter window and a ring corrector lens to reduce the abberations inherent in Schmidt optics. The camera consists of 440 hexagonal photomultipliers, each with a field of view of 1.5° in diameter. The signals are continuously digitized at 10 Ms/s, temporarily buffered and searched for shower track patterns in real time. The FD and SD systems are synchronized to about 20 nanoseconds; the data are merged offline. The light measurement is corrected for attenuation of the fluorescence light due to Rayleigh and aerosol scattering, for direct and scattered Cherenkov light and for "missing energy" due to high-energy muons and neutrinos, which carry $(10 \pm 4)\%$ of the signal away. The reconstructed energy profile is fitted with a standard Gaisser-Hillas function, which provides a measurement of the maximum depth of the shower and of the shower energy with a resolution of 8%.

The absolute calibration of the FD telescopes is known from occasionally illuminating the aperture by a flat-field source with known spectral and directional characteristics and known intensity, calibrated at the National Institute of Standards and Technology. The relative response of all FD channels is tracked frequently by illuminating the cameras from pulsed LEDs and/or Xe flashers. The atmospheric monitoring system consists of several LIDAR stations, weather recorders, balloon born meteorological probes, remote-controlled laser and dedicated aerosol monitors.

The systematic uncertainties in setting the FD energy scale sum to 22%. The largest uncertainties are due to the absolute fluorescence yield (14%), the absolute calibration of the FD (10%) and the reconstruction method (10%).

The energy threshold of the SD can be extended to below 1 EeV using FD track measurements jointly with even only one SD station.

The angular resolution of the surface detector was determined experimentally to be better than 2° for 3-fold events ($E < 4$ EeV) and better than 0.9° for higher multiplicity events, which have more than 10 EeV.

Energy Spectrum and Composition

Figure 4 (top panel) shows a detailed view of the energy spectrum obtained with the Auger Observatory for a corresponding exposure of 12,790 km^2 sr yr [5]. The ankle at 3-4 EeV and the GZK-like flux suppression starting at about 30 EeV are clearly visible. However, the latter can not yet be rigorously distinguished from the sources reaching their maximum energy.

The best estimator for the mass of a primary particle initiating an extensive air shower is the depth of shower maximum, which is directly observable with the fluorescence detector. We show in the middle and bottom panels of Figure 4 the dependence of X_{max} on energy [6]. Note that all three panels of Figure 4 have identical energy scales. There is a trend in the mean X_{max} towards higher interac-

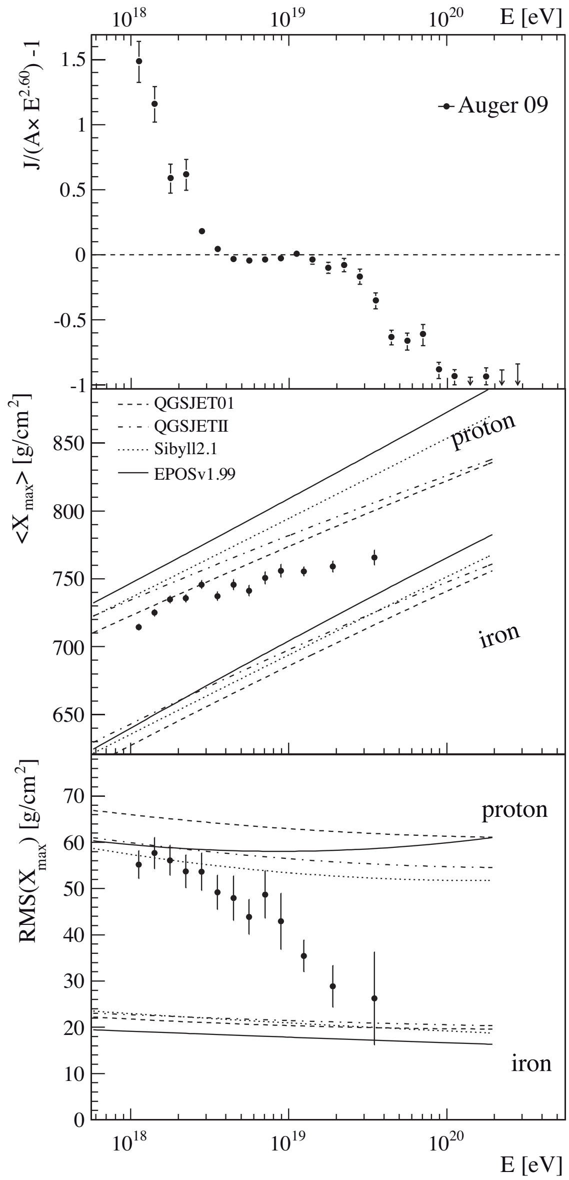

Figure 4: The Auger energy spectrum is compared to a spectrum with an index of 2.6 (top panel); SD and FD observations have been combined to cover the largest possible energy range. With increasing energy, the showers develop at greater altitudes (X_{max}, middle panel) and exhibit very small fluctuations (bottom panel). The measurements are compared to theoretical expectations using various hadronic interaction models.

tion altitudes in the atmosphere; concurrently the fluctuations of X_{max} decrease almost to the resolution limit of the FD telescopes (about 20 g/cm^2). Implicitly the graphs give an interpretation in terms of cosmic ray composition as the data points move towards the iron line above $\geq$ 10 EeV. It should be noted that increased cross sections and modified multiplicities in the first interactions early in the showers would yield similar consequences [7].

Primary photons would be deeply penetrating. The photon fraction is less than 2 percent above 10 EeV at the 95% confidence level; this limit strongly restricts the so-called top-down, non-acceleration models mentioned earlier. The signature of neutrino-induced showers would be interactions deep in the atmosphere for highly inclined showers. The current limit on the single flavour neutrino flux, is less than 5×10^{-8} GeV cm^{-2} s^{-1} sr^{-1} corresponding to neutrino energies between 0.2 and 20 EeV. Photon and neutrino limits have been published in [11].

Arrival Directions

At energies above 60 EeV the arrival directions of cosmic rays become anisotropic. The fraction of arrival directions that deviate less than 3.1 degrees from the position of active galactic nuclei listed in the Veron-Cetty and Veron catalogue (VCV) was estimated to be (69^{+11}_{-13})% from 27 events [8]. By now, the enlarged data set of 69 events above 55 EeV collected through December 2009 yields a more precise measurement of (38 ± 6)%. More data are needed to accurately constrain this parameter. The anisotropy of the arrival directions as such is a robust feature e.g. in a two-point autocorrelation function. There is also an excess of events from Centaurus A, a much debated potential source of extragalactic cosmic rays, which is only 4 Mpc away. Figure 5 shows the sky map of those most energetic events superimposed on the isotropic distribution of low-energy events [9, 10].

OUTLOOK

The southern site of the Auger Observatory will be able to measure accurately the spectrum and composition from 0.1 EeV to below 100 EeV in the anticipated next 10 - 15 years of operation. To further improve these capabilities, instrumental enhancements are currently being installed close to the Coihueco FD station. These include underground muon detectors, additional water Cherenkov detectors, high-elevation fluorescence telescopes for a larger field-of-view and radio antennae to record the geosynchrotron emission of air showers. These activities are also described in [4].

The *Telescope Array* (TA) in Utah/USA is targeting the transition region from galactic to extragalactic cosmic rays in the regime from 0.1 to 10 EeV. The array consists of 576 scintillators and three fluorescence telescopes that altogether cover almost 800 square kilometers. TA is run by a Japanese-US collaboration, taking data since spring 2008.

For a deeper understanding of the physics and astrophysics of the most energetic particles even Auger South is too small. Therefore, we are planning to construct the northern Auger site in South-East Colorado, USA, with a seven times larger aperture. The basic detector elements like water-Cherenkov detectors and fluorescence telescopes will be very similar, but adapted to newer electronics, to the somewhat colder climate and to be as cost-effective as possible. The focus of *Auger North* will be on

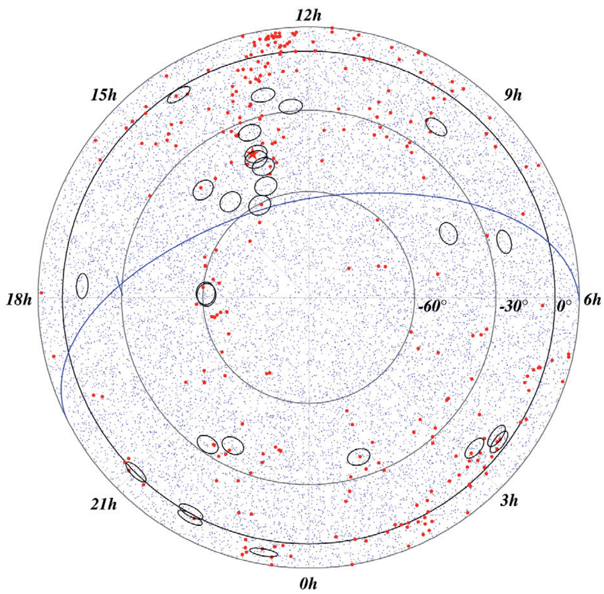

Figure 5: Equal exposure polar sky projection for events recorded by the Auger Observatory (January 2004 - August 2007, zenith angles $\leq 60°$). The 27 events with energies greater than 56 EeV are shown as black circles with radius 3.1°. Blue dots: positions of 18,000 events with energies greater than 3 EeV. Red dots: 292 quasars and AGN from the VCV catalogue with redshift $z \leq 0.017$. Red star: position of Centaurus A. Blue line: Galactic plane with the Galactic Center as a tick mark.

particles with energies above several tens of EeV. This allows for a sparse array that fills the area available of 20,000 km^2. The landscape in SE Colorado is gently rolling and open, featuring a rectangular grid of county roads with a 1-mile pitch almost everywhere. We have chosen a spacing of 2.3 km for the surface detector stations: one tank at every second road crossing, alternating in adjacent lines. The entire surface detector array will consist of 4,000 tanks, supplemented by 400 additional stations located at intermediate positions. The main array will be fully efficient above 80 EeV, while the denser *infill array* will be efficient above 10 EeV. Almost full coverage of the area will be achieved with 39 fluorescence telescopes arranged in five stations to extend the important shower profile measurements to 100 EeV [12].

A complementary approach is pursued by *JEM-EUSO*, the Japanese Experiment Module Extreme Universe Space Observatory. JEM-EUSO will hopefully be launched in 2015 to observe the fluorescence emission of air showers from the International Space Station. While its energy resolution, particle identification and angular resolution are inferior to Auger North, it provides an instant aperture of 60 times that of Auger South. Figure 6 shows that Auger North and JEM-EUSO are the first cosmic ray observatories that will be able to reach exposures of 10^6 km^2 sr yr. Such observational powers will indeed be necessary to reveal the origin and nature of the most energetic particles in the Universe. Beyond these goals – and well into the next decade – there are plans for a free-flying satellite with high resolutions (the *Super-EUSO* project).

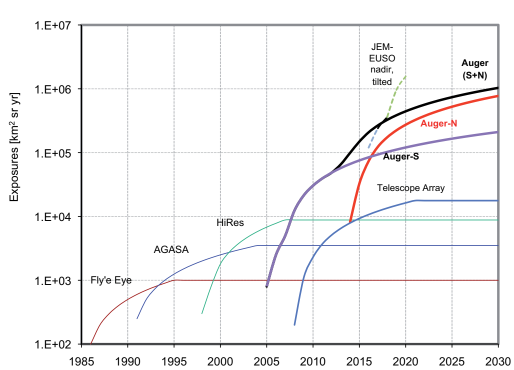

Figure 6: Exposure of major cosmic ray observatories as a function of time.

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