REVIEWS

# The dawn of the particle astronomy era in ultra-high-energy cosmic rays

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**Cosmic rays are charged particles arriving at the Earth from space. Those at the highest energies are particularly interesting because the physical processes that could create or accelerate them are at the limit of our present knowledge. They also open the window to particle astronomy, as the magnetic fields along their paths are not strong enough to deflect their trajectories much from a straight line. The Pierre Auger Observatory is the largest cosmic-ray detector on Earth, and as such is beginning to resolve past observational disagreements regarding the origin and propagation of these particles.**

In 1912, after a series of balloon flights, Hess discovered a penetrating radiation that originated in outer space. Years later, in 1926, Millikan called this radiation 'cosmic rays'. The name has survived since then, generally referring to charged particles impinging on the Earth's atmosphere. In the late 1930s, Auger and his group measured coincident signals generated by detectors separated by distances of more than a few hundred metres[1,2]: they concluded that these signals were caused by an 'extensive air-shower' (EAS) of charged particles. Auger and his co-workers assumed that the air-shower was originated by a single photon, high in the atmosphere, and used the recently developed quantum electrodynamics theory to estimate its energy, which they found to be in excess of $10^{15}$ electron volts (eV). Figure 1 shows a schematic representation of an EAS.

Cosmic rays of energies larger than about $10^{13}$ eV are small in number, and so can only be detected through the secondary particles produced when they enter Earth's atmosphere. The EAS starts with the interaction of a cosmic ray with a nucleus in the upper atmosphere. All the available energy is distributed among the secondary particles—of which there can be billions if the primary energy is above $5 \times 10^{17}$ eV—that can spread over several tens of square kilometres at ground level. Two methods are mainly used to register these particle cascades. The particle density can be sampled at the ground using an array of detectors; alternatively, the shower path can be tracked through the atmosphere, collecting the fluorescence light induced by electrons in the atmospheric nitrogen molecules.

Here we review the developments in ultra-high-energy cosmic ray (UHECR) physics over the past 15 years: we cover the controversy about the existence of the theoretically predicted suppression of the cosmic-ray energy spectrum, and its later confirmation. The most relevant topic is the discovery that the arrival direction of the most energetic cosmic rays follows the distribution of nearby extragalactic objects. This implies that their origin is not cosmological, but instead they are accelerated inside extragalactic objects, by some still unclear physical process. Three large experimental facilities—AGASA (Akeno Giant Air Shower Array), HiRes (High Resolution Fly's Eye) and the Pierre Auger Observatory—have already started what will eventually become a new era in astronomy. In the near future, further observations and more accurate instruments will identify the cosmic-ray acceleration sites and will lead to the study of the energy spectrum of individual sources. This, combined with the study of the attenuation of cosmic rays through space, could give valuable information on the cosmic microwave background. The deflection produced on the cosmic-ray path by Galactic and extragalactic magnetic fields will be an indirect tool to measure their strength. In addition, accurate measurements of the interaction of cosmic rays with the Earth's atmosphere will hint at the particle physics interaction models, at an energy range beyond what can be achieved in

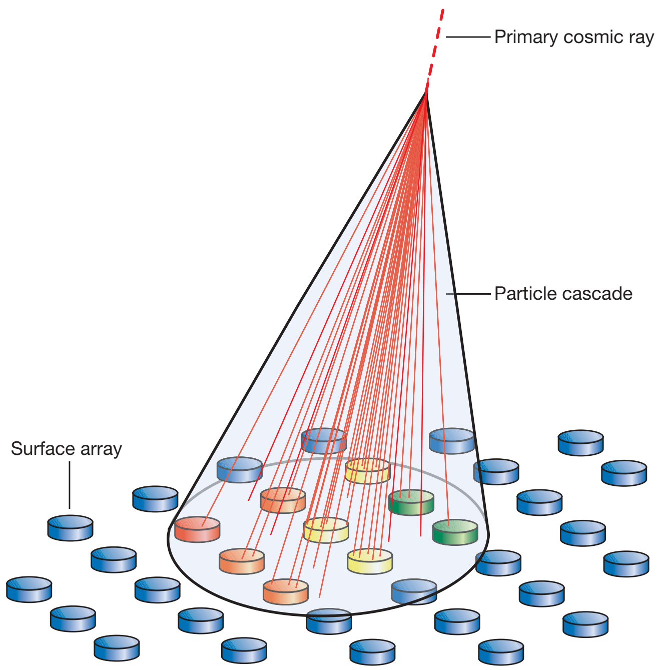


**Figure 1 | Scheme of an extensive air-shower.** The primary cosmic ray (dashed line) undergoes a nuclear interaction in the upper atmosphere (typically 20 km above sea level), producing a cascade of elementary particles (represented as solid red lines within a conical shape). These particles propagate across the atmosphere and could reach ground level. The cascade footprint at the ground could be of tens of square kilometres. A network of particle detectors at ground level (surface array) can detect the arrival of the particles, allowing reconstruction of the whole cascade. Different colours in the scheme represent different arrival times of the particles.

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human-made accelerators. These observations are within reach of the current and next-generation observatories, and will herald the dawn of the era of charged-particle astronomy.

## Properties of cosmic rays

The observed cosmic-ray energy spectrum spans from $10^8$ eV to more than $10^{20}$ eV. Particles with energies lower than $10^{10}$ eV mainly come from the Sun, as the solar wind prevents particles in that energy range from reaching the Earth from outside the Solar System. For energies higher than $10^{18}$ eV, a convincing explanation of the acceleration processes and sources is still unknown. Some theories suggest that these cosmic rays originate in stellar winds within our Galaxy and later accelerate in supernova shocks or similar high-energy environments[3]. Active galactic nuclei (AGN), galaxies with very intense emission in a broad wavelength range, are possible source candidates of UHECRs above $10^{19}$ eV (ref. 4), but so far there are only experimental hints suggesting this.

The cosmic-ray flux follows a power law ($E^{-\gamma}$) as a function of energy $E$, with an approximate index $\gamma = 3$. This index value remains remarkably constant, showing only small variations across the whole measured cosmic-ray energy spectrum.

At the highest energies, above $10^{20}$ eV, the estimated number of particles is only a few per km$^2$ per millennium. This extremely low flux calls for the construction of huge observatories, covering a very large area with detectors. For instance, the Pierre Auger Southern Observatory in Argentina covers 3,000 km$^2$, which is about 30 times the size of the district of Paris.

Cosmic rays with energies above $4 \times 10^{19}$ eV cannot travel through space without being attenuated[5,6]. Propagation is mainly affected by the presence of the cosmic microwave background radiation, consisting of photons with a black-body radiation distribution corresponding to an equivalent temperature of 2.7 K. In the rest frame of an extremely energetic proton, these low-energy photons are seen as very high energy photons ($\gamma$-rays), of about $10^8$ eV. If the photon energy in the rest frame is above 150 MeV, pion-production reactions become possible. The proton loses energy in each reaction, reducing the mean distance it can travel undisturbed to about 50 Mpc. This effect produces a dip in the spectrum, known as the 'GZK suppression' (named after Greisen, Zatsepin and Kuzmin, who predicted its existence), and it reduces the number of high energy particles able to arrive at Earth, if originated at larger distances.

The HiRes observatory data suggested the presence of suppression in the flux of cosmic rays in the GZK energy region[7], whereas the AGASA collaboration announced that the cosmic-ray spectrum continued, with a power law dependence, above GZK energies[8]. This last result was revisited a few years later, without being able to arrive at a definite conclusion owing to the limited number of events in the GZK energy region, even though the existing, limited data collected by AGASA is still being re-analysed[9,10].

The Pierre Auger Southern Observatory data seem to agree with the HiRes result in the GZK energy region[10], resolving the controversy between the two previous experimental results. The observation of the GZK suppression[11] is another interesting result. The larger data set of the Auger Observatory made it also possible to establish a correlation between some high energy events and AGN (or any other astronomical objects that follow the same spatial distribution) closer than 75 Mpc to the Earth[12]. For protons with energy larger than $6 \times 10^{19}$ eV, the magnetic deflection of the trajectory of the cosmic rays is only a few degrees[12], hence enabling the possibility of particle astronomy. This small deflection would imply that the particles 'point back' to their sources, making it possible to identify the origin of cosmic rays and even study the spectra of individual sources. By studying the distribution of cosmic-ray arrival directions (such as clustering, thread-like structures, and so on), it would be possible to analyse the properties of Galactic and inter-galactic magnetic fields.

## The AGASA observatory

AGASA[13] was located at Akeno, Japan. It ran in full operation mode from 1993 to 2004, being able to take data continuously, independently of weather conditions. Each ground station, composed of plastic scintillators, sampled the secondary particles of an EAS. The trigger time of each individual station was used in the reconstruction of the EAS arrival direction, while the energy measurement was based on the number of particles at each station.

The energy of a shower detected using a ground array is not measured directly. The particle density at a given distance from the EAS axis is correlated with the energy of the primary cosmic ray through computer simulations. The models used in the simulations are based on the knowledge about interactions acquired in particle accelerator experiments. This means that the models extrapolate the physical processes to several orders of magnitude in energy beyond what has been measured until now. One of the Large Hadron Collider experiments (LHCf) will be dedicated to reducing the uncertainty in hadron interaction models of cosmic-ray showers, by measuring the forward particle production in proton interactions[14]. Apart from this, the computational effort of producing and tracking about $10^{11}$ particles is too large to be practical. Hence, only a statistically representative sample of the EAS secondary particles is propagated to the ground in the simulation. All these facts lead to an energy measurement that is strongly model dependent, and to large uncertainties in its value.

## The HiRes observatory

The HiRes Fly's Eye[15] was located in Dugway, Utah, USA. HiRes commissioned its first location in 1997 and its second location in 1999. Both locations were decommissioned in 2006. This observatory collected fluorescence light induced in the atmosphere by the passing EAS. The total brightness of an EAS, in fluorescence light, averages a few watts. The amount of light collected is so faint that these detectors can only operate on clear, moonless nights. Typical observation duty factors of fluorescence detectors lie between 10% and 15%.

Each of the HiRes locations had mirrors that focused the fluorescence photons into a light sensor array, or 'camera'. It is conceptually similar to a CCD camera, with each light sensor playing the role of one pixel. By considering the relative trigger times and geometric pattern of the pixels in the camera, it is possible to reconstruct the arrival direction of the shower. The energy is calculated by integrating the total amount of light measured at the detector location. The total number of photons induced in the atmosphere by the EAS is proportional to the total available energy, that is, the energy of the primary cosmic ray. Some particles in the cascade do not induce fluorescence light and the total energy of the EAS must be corrected to account for this fact. The atmospheric conditions are other factors to include when estimating the primary cosmic-ray energy. An atmospheric attenuation correction, based on the distance from the EAS to the detector, needs to be applied.

## Discrepant results

The limited sample of cosmic rays in the GZK energy region, together with intrinsic differences in the way each experiment measured the cosmic-ray energy, set the stage for a controversial difference between the measured spectra.

A comparison of both measured spectra is shown in Fig. 2, where the discrepancy is clear. The AGASA data seemed to favour the absence of a suppression, while HiRes spectrum followed the expected curve. Both results should be interpreted carefully, as the calculations involved are not straightforward and, again, the number of detected events was not enough to firmly establish either claim[16].

When computing a cosmic-ray spectrum, it is critical to calculate the instrument exposure, or time-integrated collection area. In the case of AGASA, the exposure is reduced to the convolution of the detector array geometrical area, the acceptance solid angle and the effective running time. The acceptance of a surface array, like AGASA, becomes

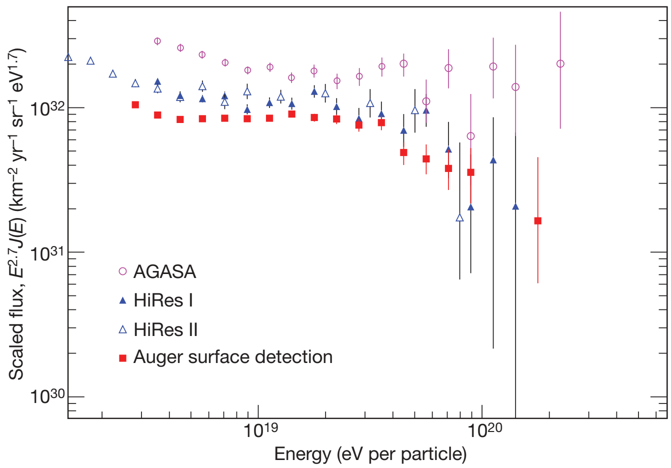


**Figure 2 | UHECR data from different experiments.** **Comparison between AGASA (circles), HiRes monocular spectra (open and filled triangles correspond to each HiRes location) and Pierre Auger Southern Observatory. Error bars are 1$\sigma$.**

constant with energy, once its trigger efficiency reaches 100%. The cumulative exposure for this detector is about 1,600 km$^2$ sr yr (ref. 17).

A fluorescence detector requires a more complicated exposure calculation. The collection volume is a hemisphere (centred at the detector location), the radius of which indicates the maximum observation distance for a given EAS. This distance changes with the atmospheric conditions (atmospheric aerosols, cloud coverage, position of the clouds) and depends on the EAS energy. The acceptance of a fluorescence detector, like HiRes, is a function of the EAS energy (the brighter the EAS, the further away it can be detected). This implies that, in order to calculate the energy spectrum of an EAS, it is necessary to accurately know how the instrument acceptance depends on the EAS energy and the atmospheric conditions at the time of measurement. It is very difficult to deduce the exposure of HiRes from the published results, but it is quoted as "more than twice that of AGASA above the GZK-threshold"[7].

In any case, both these experiments have statistically limited data samples, given the extremely low cosmic-ray flux at those energies[16]. In response to the AGASA results, numerous speculations about how cosmic rays could avoid energy loss on their way to Earth were proposed. Either new particles[18,19] or interactions with magnetic fields[20] were invoked to avoid the problem. These articles are just a small sample of a long list showing different (and sometimes quite ingenious) arguments.

Besides measuring the energy spectrum, both experiments analysed the arrival direction distributions of cosmic rays. An '$n$-plet' is defined as a set of $n$ independent events whose arrival directions are the same, within experimental uncertainties. The AGASA collaboration found 5 doublets and 1 triplet[21] in their data sample, where only 2 doublets were expected statistically. This result was not confirmed by HiRes[22]. On the other hand, correlations were found in the HiRes sample with the locations of BL Lacertae objects (AGN with their jets pointing towards Earth)[23], although they have not been confirmed by an independent data sample. It should be remarked that anisotropy in the arrival direction of cosmic rays is not expected at lower energies. However, at higher energies—combining data from different observatories—an excess of events coming from the supergalactic plane (a plane defined by the locations of the galaxies in the local cluster) was found for events with energies above $4 \times 10^{19}$ eV, giving a hint that the origin of UHECRs is most likely to be extragalactic[24]. This result was independently suggested later by analysing the shape of the cosmic–ray spectrum[25,26].

The relatively low exposures of these experiments could only provide hints about the arrival direction of the cosmic rays, making it possible to search for clustering and sources, but not to confirm them. Still, these results were extremely important in that they showed anisotropy studies (and potentially the identification of cosmic-ray sources) to be within reach.

## The Pierre Auger Observatory

The Pierre Auger Southern Observatory[27], schematically shown in Fig. 3, is located in the province of Mendoza, Argentina. It covers an approximate area of 3,000 km$^2$, which makes it the largest cosmic-ray observatory to date. Its northern counterpart will be built in the vicinity of Lamar, Colorado, USA. When finished, the joint instruments will have full sky coverage as observed from both hemispheres. The Southern Observatory has been collecting cosmic-ray data since 2004, while increasing its size up to the installation of the last surface detector on June 2008. As of 31 August 2007, the accumulated exposure of the Southern Observatory is 9,000 km$^2$ sr yr (ref. 28). The yearly accumulated exposure is about 6,000 km$^2$ sr yr and the observatory is expected to operate for a total of 20 years.

This observatory combines the techniques used in previous experiments, by means of a 'hybrid detector', that is, having a fluorescence detector and an array of surface detectors working together. The fluorescence detector follows the shower cascade across the atmosphere and the surface detector array—in this case water Cherenkov detectors—detects the particles on arrival at ground level. Hybrid measurements can set an absolute energy scale, improve the determination of the primary particle type and give better energy and angular resolution[27]. This approach provides a model-independent energy calculation, using the fluorescence detector data together with the simple surface array aperture calculation.

In hybrid mode, for any given EAS measured simultaneously by both instruments, the energy deposited in the atmosphere—as recorded by the fluorescence detector—is then related to a surface detector energy parameter. Then, this model-independent correlation can be used as energy calibration for events measured only with the surface detector array[29].

The Pierre Auger Collaboration is taking advantage of the unique characteristics of the observatory. Although the limit is arbitrary, EAS detected by water Cherenkov arrays are typically reconstructed only up to 60°. Auger Collaboration members have developed analysis techniques to extend the acceptance up to 75°, which increases the

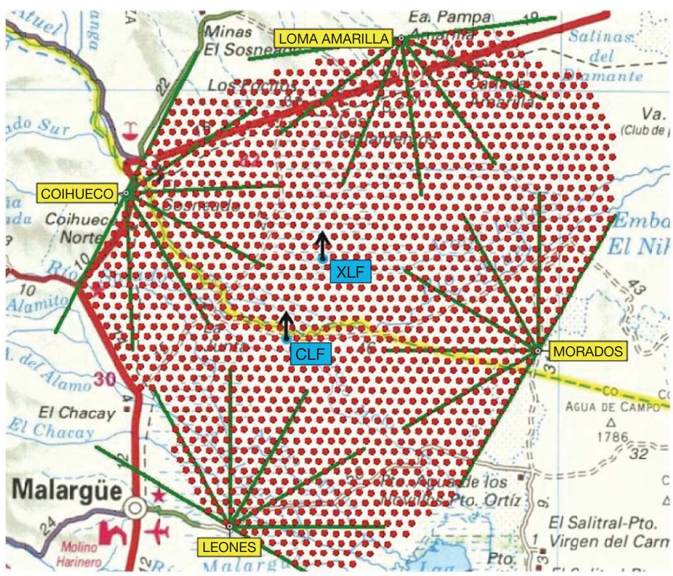


**Figure 3 | The Pierre Auger Southern Observatory.** It consists of an array of 1,600 surface detectors (red filled circles), complemented by 24 fluorescence detectors, grouped in four buildings (yellow labels; Leones, Morados, Loma Amarilla and Coihueco). Green lines represent the field of view of each detector. Two laser facilities (blue labels; CLF and XLF) are available for energy calibration and atmospheric monitoring. Observatory information is superimposed on a map of the area.

instrument exposure even further[30]. As a comparison, plastic scintillator arrays (like AGASA, or the Telescope Array in Utah, see below) typically limit their reconstructed events up to 45°.

## Evidence for the GZK suppression

Results recently published by the Auger Collaboration[11] report the existence of a deficit of cosmic rays at the highest energies. Still, this result alone is not enough as to prove that the GZK suppression has been observed. It could be that the energy spectrum is limited by the maximum energy available at the cosmic-ray acceleration sites.

When the evidence on the deficit in the flux of cosmic rays is put together with the energy at which the correlation with nearby extragalactic objects[28] sets in, one could then argue that the GZK suppression has been observed. If objects beyond an approximate distance of 75 Mpc were to be included in the analysis, the correlation would very rapidly diminish.

Although both HiRes and the Pierre Auger Southern Observatory have observed a suppression in the cosmic-ray flux above an energy of approximately $4 \times 10^{19}$ eV, differences still exist in the measured spectrum index and the overall energy normalization. The energy scales of these two observatories differ by about 17% (ref. 31).

## The sources

One of the main questions to be answered regarding UHECRs is how these particles can be accelerated to such energies. The size of the acceleration region and the magnetic field present in it must follow a relation, usually represented in a Hillas plot like that shown in Fig. 4. Only a few astrophysical objects could then be potential sources.

Arguably, the most relevant recent observation has been the discovery of a correlation between cosmic-ray arrival directions and nearby extragalactic objects[12,28]. The correlation found in the Pierre Auger Southern Observatory data becomes significant for cosmic rays above $5.7 \times 10^{19}$ eV and AGN within 75 Mpc. With those

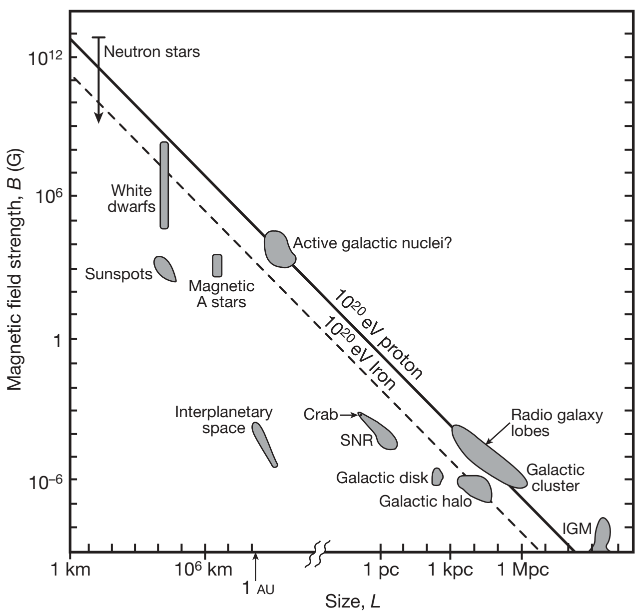


**Figure 4 | Hillas diagram.** Non-exotic acceleration processes require a particle to be confined within a region (of size $L$) where magnetic field shocks are present (with a field intensity value of $B$). Once the particle reaches its maximum energy, then the magnetic field is not able to keep the particle confined within the acceleration region and the particle escapes. This gives an approximate value for the maximum achievable energy of $E_{max} = BL$, shown as a solid/dashed line for a $10^{20}$ eV proton/iron nuclei, respectively. We show data for a variety of astrophysical objects; only those above the line can accelerate particles to energies into the GZK region. Crab indicates the Crab nebula; SNR, supernova remnant, IGM, intergalactic magnetic field.

parameters, 20 events (out of a total of 27) lie within 3.1° from an object listed in the Veron-Cetty-Veron catalogue[32].

AGN have traditionally been considered as possible candidates for cosmic-ray acceleration sites. However, any other astrophysical object close enough to Earth to avoid the GZK suppression, with a spatial distribution similar enough to that of AGN, could be the source.

The AGN hypothesis seems to be supported by the correlation found between the arrival direction of cosmic rays reported by the Auger Collaboration[12] and the positions of the Swift hard X-ray catalogue of AGN, when weighted by the X-ray flux and constrained to distances less 100 Mpc (ref. 33). At the same time, using the same events measured by the Pierre Auger Southern Observatory, a correlation was also found with the HIPASS catalogue of H I spiral galaxies (when weighted by their H I flux)[34]. The latter results do not contradict the correlation found with AGN, as all these objects trace the distribution of matter. The hypothesis of H I galaxies as cosmic-ray sources is interesting, as it would explain the lack of events from the Virgo cluster (which is not rich in H I galaxies).

HiRes members have searched their data for correlations[35] based on the Pierre Auger Southern Observatory parameters, and their analysis does not support the result published by the Auger Collaboration. Reference 31 shows that if corrected by the energy mismatch between both experiments, HiRes would have only 5 events in their stereo data sample, which might not be enough as to establish or reject any correlation.

## Open questions

Despite having measured a suppression in the spectrum compatible with the GZK suppression and arrival direction anisotropies (or perhaps because of those facts), some exciting and intriguing questions still remain to be solved.

**Sources and acceleration models**. Nearby extragalactic objects have been found to correlate with the arrival direction of cosmic rays, but it is not yet possible to study the energy spectrum of individual sources. Such a spectrum would lead to a better understanding of acceleration processes at the sources. At the same time, the search for other potential sources should continue. Cosmic rays could be generated by different astrophysical objects.

**Energy spectrum**. The GZK suppression is produced by the interaction of nucleons with photons, at energies higher than $4 \times 10^{19}$ eV. At energies higher than $3 \times 10^{20}$ eV, the interactions become much less probable. Hence, cosmic rays with those energies could propagate almost undisturbed through space, allowing the study of the Universe at extreme energies. This feature, predicted by quantum physics, is known as the 'GZK recovery'. Observing it would prove quantum physics at an energy range that has not been explored before. The lack of a GZK recovery could imply new physics.

**Mass composition and particle physics.** A very important point to be studied is the mass composition of cosmic rays. This will either prove or reject different acceleration and propagation models, which favour either light or heavy primary particles. Moreover, at these high energies, cosmic-ray interactions with atoms in the upper atmosphere are in the range of a few hundred TeV (in the centre of mass frame). Studies of shower development in the atmosphere (known as elongation rate) will give an opportunity to unveil features of hadronic interactions at these energies, which are more than one order of magnitude higher than those achievable by the Large Hadron Collider, the most powerful human-made particle accelerator[36].

**Magnetic fields**. Magnetic fields could be studied by looking at the arrival direction pattern of cosmic rays as a function of energy. If 'strings' of events were identified, their relative deviation at different energies would allow us to set limits (or possibly even measure) the strength of Galactic and extragalactic magnetic fields.

A larger set of events, measured with good resolution, will answer several questions. As it is true for so many scientific disciplines, the main problem to be solved regarding the study of UHECRs is obtaining a significantly larger number of events.

## The future

The Pierre Auger Southern Observatory is the largest-aperture observatory currently taking data and its exposure is larger than that of any previous detector. There is a proposal to increase the size of the projected Northern Observatory to cover an area 7 times larger than that of the Southern Observatory.

The Telescope Array in Utah, a hybrid instrument combining a surface scintillator array and fluorescence detectors, is the only observatory in the Northern Hemisphere currently taking data in this energy regime. Its yearly cumulative exposure will depend on the final operation conditions, but it could be estimated to be about 1,400 $km^2$ sr yr (ref. 37).

New techniques and observation methods are being considered. The collection of fluorescence light with space-based instruments, looking down into the Earth's atmosphere, has been proposed. JEM-EUSO[38] and OWL[39] are examples of this technique. Radio-wave detection of EAS is also currently being developed[40].

The past decade has proven fruitful and exciting in cosmic-ray physics. We have witnessed revisions and improvements in the instrumental techniques, which in turn have paid off by establishing the existence of the GZK suppression and by the discovery of anisotropies in the cosmic-ray arrival directions. In cosmic-ray physics, discoveries have been achieved by seeking the largest exposure possible. History has shown us that in this field, exposure matters.

In the near future, within 4 years or so, the Pierre Auger Southern Observatory should have observed about 100 events above $\sim 5 \times 10^{19}$ eV. In contrast, the proposed Pierre Auger Northern Observatory could be collecting the above-mentioned statistics every 9 months. In 20 years of combined operation, about 2,000 events (above $\sim 5 \times 10^{19}$ eV) could have been observed. Such data from the Northern and Southern Observatories could be used to accurately search for point sources, to study the energy spectra of different sources, and to understand Galactic and extragalactic magnetic fields, as well as to investigate and perhaps uncover particle physics beyond accelerator energies. A new window to the Universe has been opened; we are witnessing the dawn of the particle astronomy era.


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