Ultra high energy cosmic rays
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Ultra High Energy Cosmic Rays (UHECRs) represent the most energetic source of elementary particles available to scientists. They have macroscopic energies, exceeding $5 \times 10^{19}$ eV, and as yet unidentified sources. Unfortunately, their flux is as low as one particle per century per square kilometre, requiring dedicated detectors with huge apertures to obtain high-quality and statistically significant data-sets. Over the last three to four decades, a few tens of events at extreme energies were detected by ground-based cosmic ray detectors, opening a new window in the field of astroparticle physics. In this article, the physics of cosmic rays is reviewed briefly. We present a short history and the present status of the field mainly from an experimental point of view. Special attention is given to the Pierre Auger Observatory, the world’s largest operating hybrid detector. The most recent and fascinating results are also presented and discussed. Finally, some attention is given to the next generation of detectors devoted to the exploration of the highest energy ranges, which is likely to dramatically increase our knowledge about UHECRs in the near future.

Keywords: ultra high energy cosmic rays; cosmic ray flux; cosmic microwave background; acceleration; UHECR sources; GZK cut-off, magnetic fields; extensive air shower; surface arrays; fluorescence detectors; energy spectrum; arrival directions; active galactic nuclei; composition; photon flux limit

1. Introduction

Cosmic rays hit our atmosphere like a never ending rain. Despite the fact that we neither see them nor feel them, we are constantly bombarded by ionising cosmic ray radiation. The energies of cosmic rays span over 12 orders of magnitude, extending to tens of Joules per particle. And so does their flux, decreasing from almost one particle per square centimetre per second at low energies to a few particles per square kilometre per millennium at extreme energies. The energy spectrum of cosmic rays above $10^{10}$ eV, where the magnetic field of the Sun is no longer a concern, is almost featureless (see Figure 1). It is nearly a power law with a slight steepening near $3 \times 10^{15}$ eV and a slight flattening near $3 \times 10^{18}$ eV. The two features are popularly called the ‘knee’ and the ‘ankle’, respectively.

In this article we will focus on experimental efforts to measure and study the most energetic particles in the Universe. Their energy exceeds the energy of the most powerful accelerators ever built by scientists on the Earth (LHC at CERN for example) by seven orders of magnitude. Their centre-of-mass energy in collisions with nuclei in the atmosphere is almost two orders of magnitude higher than the interaction energy in the most powerful hadron collider in the world. It seems that these magnificent messengers from the Universe are freely given to scientists by Mother Nature. Unfortunately, you never get anything for free. Due to the very low flux of Ultra High Energy Cosmic Rays (UHECR) there are not many reaching the Earth. Thus, while studying them, astroparticle physicists are faced with extreme experimental difficulties and have to build large-scale observatories covering thousands of square kilometres.

The scientific field of cosmic rays at extreme energies has long provided more questions than answers. It has been over 40 years since the detection of the first cosmic ray with an energy greater than $10^{20}$ eV by John Linsley [1] and eight years since this subject was last reviewed by Alan Watson [2] but we still do not know the origin of these cosmic bullets. The exact determination of the energy spectrum at its upper end is only the beginning of the exploration of the realm of UHECRs. Physicists would like to know what they are. Are they protons, light or heavy nuclei, or maybe photons? Are neutrinos part of the UHECRs? What are the sources of UHECRs and what is their production mechanism? Do we have enormous accelerators in our astronomical neighbourhood or are UHECRs remnants of exotic and unknown processes from the beginning of our Universe? At present, we do not know a definite answer to these questions. However, we may be on the verge of rapid progress.

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2. Historical background

The history of research in cosmic rays is fascinating. It has produced several Nobel prizes and is now stimulating experiments on a global scale. The discovery of cosmic rays is attributed to Victor F. Hess who in 1912 performed several ascents with hydrogen-filled balloons up to altitudes of 5 km [3]. Hess found an increase of ionising radiation with increasing altitude and he concluded that radiation penetrates into the atmosphere from the outer space. For his discovery, he shared the 1936 Nobel prize.

In 1938, Pierre Auger and Roland Maze showed that cosmic rays separated by distances as large as 20 m arrived in time coincidence, indicating that observed particles were secondaries from a common source [4]. Subsequent experiments at the Jungfraujoch in the Swiss Alps showed the same phenomenon even at distances up to 200 m [5]. This led Pierre Auger to conclude that these events were caused by extensive air-showers (EAS) of charged particles originating from a single primary particle high in the atmosphere. He estimated the energy of the primary particle to be in excess of $10^{15}$ eV. Auger and his colleagues discovered that in nature there exist particles with an energy around $10^{15}$ eV at a time when the largest energies from natural radioactivity or artificial acceleration were just a few times $10^6$ eV.

This discovery was followed in the mid-1940s by the construction of large detector arrays with fast time resolution. For most investigations large detector arrays with short time resolution were required. Principles of detection of cosmic rays with large arrays of detectors as well as with measurements of fluorescence in the atmosphere will be given in Section 4. Early detectors were comprised of Geiger-Muller counters. Progress in the development of photomultiplier tubes led to the application of scintillation counters and Cherenkov detectors. The most important result of these and later experiments was that the energy spectrum follows a simple power law $dN/dE \sim E^g$ over a large range of the energies. In the late 1950s Kulikov and Christiansen [6] discovered a kink in the energy spectrum at around $10^{15}$ eV. This structure in the cosmic ray spectrum is now known as the ‘knee’ and it is thought to be the consequence of a limitation on the particle acceleration capability of typical galactic supernova remnants.

The experimental efforts culminated in the large cosmic-ray detector built first by John Linsley and collaborators at Volcano Ranch in New Mexico, USA. This detector was an array of scintillation counters spread over an area of 10 km$^2$. The primary cosmic ray particles were detected by the air showers they produced in the atmosphere. In 1963 they reported a shower produced by a cosmic ray of energy exceeding $10^{20}$ eV [1]. John Linsley was not only an excellent experimentalist but also a lucky man: the chance of detecting an event of this energy after running his 10 km$^2$ array for one year was of the order of 1%.

Linsley’s ground array was the first of a number of large cosmic-ray detectors that have measured the cosmic-ray spectrum at the highest energies. Larger air-shower arrays were built in Europe (Haverah Park [7,8]), Australia (SUGAR [9–11]), Japan (AGASA [12,13]) and Russia (Yakutsk [14]). In the 1980s the first fluorescence light cameras were built and operated in Utah [15]. These experiments discovered another feature in the cosmic-ray spectrum in the early 1990s, today known as the ‘ankle’. It possibly indicates a transition to cosmic rays of extragalactic origin.

We should not forget to mention that cosmic rays played a crucial role in the development of particle physics. For many years they were the only source of energetic particles available to the experimentalists. Only after the Second World War did scientists build accelerators that could achieve high energies and, even more importantly, high fluxes for consequently higher interaction rates. So, it is not surprising at all that many of the great discoveries in particle physics came from the observation of cosmic rays. Already in the 1930s, investigations of cosmic radiation led to the discovery of new elementary particles. Positrons were found in 1933 by Carl D. Anderson [16] and the muon four years later [17]. The pion was discovered in 1947 [18] by exposing nuclear emulsions to cosmic radiation at high altitudes. Unknown and unstable hadrons were found in cosmic-ray interactions using balloon-borne emulsion chambers [19] in 1971 which were later, after the discovery of charm at accelerator experiments, identified as D mesons [20]. From 1970 on, the field of particle
physics was dominated by accelerators. But UHECR are coming back into the game since their energy exceeds the energy of man-made accelerators by several orders of magnitude. Unfortunately, the UHECR flux is very low, inspiring calls for large-area detectors, which have now become feasible with present technologies. Today, experimental and theoretical UHECR research represents an important part of astroparticle physics, a newly emerging field of science. A detailed overview of the history of astroparticle physics can be found in [21].

3. Astrophysical background

UHECRs originate from outer space. Their origin is most probably extragalactic. The mechanism of their production is not known. They might be produced by astronomical accelerators or they might be remnants of processes that occurred during the evolution of the early Universe. This latter case (‘Exotic Sources’) would require ‘new physics’ and the existence of unknown heavy particles. Before being detected at Earth, they travel large distances through a space full of Cosmic Microwave Background (CMB) photons as well as a magnetic field of varying strength and orientation. In the following, we will discuss the limitations set by their production and propagation.

3.1. Conventional acceleration

In known astrophysical contexts it is also a challenge to explain the acceleration of particles to the energies above $10^{20}$ eV. The suggested models for acceleration fall into the following classes: acceleration in strong fields associated with accretion discs and compact rotating objects, and shock-wave acceleration in catastrophic events.

Almost independently of how the particles are accelerated, the upper bound of the energy gained is determined by balancing the acceleration time with the escape time from the acceleration site. In 1984 Hillas showed [22] that irrespective of the details of the acceleration mechanisms, the maximum energy of a particle with charge $Ze$ within a given ‘accelerator’ of size $L$ is of the order

$$E_{\text{max}} \approx \left( \frac{B}{1\mu G} \right) \left( \frac{L}{1pc} \right) \times 10^{15}\text{ eV},$$

where $B$ is the magnetic field inside the acceleration volume and $\beta$ is the velocity of the shock wave or the efficiency of the acceleration mechanism. The magnetic field needs to be large enough to confine the particles within their acceleration site and the site must be sufficiently large for particles to gain enough energy before they escape. These simple requirements already rule out most astronomical objects in our Universe and are nicely represented in the Hillas diagram shown in Figure 2.

In any acceleration site, energy loss mechanisms always compete with the gain of energy. With first-order Fermi shock acceleration [23], the acceleration time is proportional to the mean free path for scattering in the shock wave, which itself is approximately inversely proportional to the magnetic field strength. Therefore, a certain magnitude of magnetic field is required, not only to confine the particles within the site, but also to accelerate particles quickly. However, too strong a magnetic field also induces problems for particle acceleration, because it can cause protons to lose energy via synchrotron radiation. Other strong energy losses are caused by collisions with photons and/or matter at the acceleration site. This leads to additional requirements that the site must have sufficiently low densities of radiation and matter. This additionally limits the list of possible candidates.

Most of the galactic objects are excluded simply because they are too small and/or have magnetic fields that are too weak. Only a few extragalactic objects such as Active Galactic Nuclei (AGN) and radio galaxies remain as possible candidates. This fact is the basic reason why many favour the extragalactic origin of UHECRs.

3.2. Exotic sources

UHECR might be products of processes not requiring acceleration. So called ‘top-down’ scenarios have been proposed by many authors involving, for example, relics of symmetry breaking phase transitions in the early Universe such as cosmic strings or magnetic...
monopoles, characterised by a common name as topological defects (see [24] for a review). If such defects exist, they may have produced particles with energies up to the Grand Unification Theory (GUT) scale, i.e. of the order of $10^{25}$ eV. Such processes would produce a large cascade of energetic photons, neutrinos and light leptons with a very small proportion of protons and neutrons. Heavy nuclei are highly unlikely products of the hadronisation process. One expects therefore that gamma rays would be the major component of UHECR produced at energies above $10^{20}$ eV by top-down mechanisms.

The basic problem of this scenario is that such processes are exotic. The absolute intensity is up to now completely unknown but is expected to be low. Nevertheless, detection of $\gamma$ rays above $10^{20}$ eV and/or extremely high energy neutrinos above $10^{19}$ eV would be a general signature of topological defects.

### 3.3. Propagation of UHECR in space

UHECRs travel from their sources to the Earth. Understanding the propagation phenomena is of extreme importance since it sets constraints on possible sources and provides hints for the most effective way of searching for them.

#### 3.3.1. The GZK cut-off

Soon after the discovery of the CMB, it was pointed out by Greisen [25] and by Zatsepin and Kuz'min [26] that the CMB may render the Universe opaque to cosmic rays of sufficiently high energies. The threshold for pion photo-production (via the $\Delta$ resonance) through the reaction of protons or neutrons with $2.35 \times 10^{-4}$ eV CMB photons occurs at the energy of approximately $10^{19.7}$ eV. Successive interactions reduce the energy of a nucleon until it falls below threshold. Characteristic attenuation lengths for protons at the highest energies are of the order of 10 Mpc, which is a small distance on the cosmological scale. Energetic nuclei and photons also lose energy by photo-disintegration and pair production, respectively. Only neutrinos or unknown neutral weakly interacting particles would be immune to these processes, but their interaction probability with atoms in the atmosphere would also be negligible unless the cross-section becomes strong at high energy [27,28]. Thus, there exist limits to the distance to the sources of the most energetic particles. Almost independently of the initial energy of a proton, as soon as it is above the GZK cut-off, it will be found with an energy less than $10^{20}$ eV after propagating through a distance of 100 Mpc. The observation of a cosmic ray proton with energy greater than $10^{20}$ eV implies that its distance of travel is less than 100 Mpc and that its initial energy at its source had to have been much higher. The GZK cut-off should be manifested in the observed spectrum as a strong suppression above $10^{19.7}$ eV, with a possible pile-up in the differential spectrum just below that energy threshold. The detailed shape of the spectrum will depend on the source distribution in space and time as well as the initial production spectra. On the other hand, any evidence of beyond-GZK cosmic rays raises questions on how the cut-off could be violated.

#### 3.3.2. Magnetic fields

Possible UHECR sources can be located by the reconstruction of the incident direction of cosmic rays and by checking the data for images of point sources or correlations with distributions of astrophysical objects in our vicinity. If we assume that UHECRs are protons, the trajectories will be bent in the magnetic field when propagating through the Universe. We will show that deflection angles are small at energies above GZK cut-off, opening a window to proton astronomy.

There are a limited number of methods to study the magnetic fields on galactic or extragalactic scales [29]. The magnetic field structure of our galaxy is thought to be rather well understood. Most of the models, mainly differing in details, foresee concentric field lines with a few $\mu$G strength and a rapidly decreasing field in the halo.

A galactic magnetic field with $\sim \mu$G intensity can no longer confine cosmic-ray protons with energies greater than $10^{19}$ eV in the galactic disc since the Larmor radius of a proton at that energy becomes greater than the thickness of our galactic disc which is on average around 1000 light years. This means that any galactic proton can easily escape from our galaxy, provided that the magnetic fields do not extend into halo. This again favours the hypothesis of extragalactic origin of EHECRs.

Information on the extragalactic magnetic field strength is even more difficult to gather. The study of extragalactic fields is mainly based on the Faraday rotation measurements of the linearly polarised radio sources. Because of the faintness of extragalactic signals, our knowledge of the strength and coherence distances of large scale extragalactic fields is quite poor and only upper limits over large distances can be extracted. An educated guess gives an upper limit of 1 nG for the field strength and coherence lengths of the order of 1 Mpc. This would result in observed deviations of the order of $1^\circ$ for $10^{20}$ eV protons.

Since the angular resolution of cosmic ray detectors is comparable to or much better than this value, one can expect to be able to locate point sources, if they exist, or at least to establish correlations with large-scale astronomical structures.
4. Experimental techniques

For an incident UHECR, the atmosphere acts as a calorimeter with varying density and a vertical thickness of approximately 26 radiation lengths or 11 interaction lengths. It is a very complicated calorimeter having properties that change in space and in time, influencing the development of the signal and so must be monitored very carefully.

In the following, we will present the basic properties of the performance of this calorimeter. A detailed overview of extensive air-shower measurement techniques can be found in [30].

4.1. Development of the signal

An excellent introduction to cosmic rays and their interactions may be found in [31]. Many aspects of the development of showers in the atmosphere may be understood in the context of a simple three-component model [32] (see explanation below and Figure 3).

When an incoming UHE proton interacts with an air nucleus in the upper atmosphere, a leading baryon is produced along with several pions. The pions then propagate through the atmosphere until they interact again or decay. The competition between interactions and decays depends on the atmospheric density and on the particle Lorentz factor $\gamma$, which diminishes as the shower energy is divided among an increasing number of particles. For neutral pions, decays are dominant at all Lorentz factors of interest. Photons emitted in this decay initiate an electromagnetic cascade. For charged pions, interactions dominate at high Lorentz factor. When the charged pions interact, pions of reduced Lorentz factor are produced, about a third of which are $\pi^0$. Charged pions continue to interact until their energy is reduced to $\sim 20$ GeV where decay to muons starts to dominate, and neutral pions decay to photons that join the electromagnetic cascade. Since both the baryonic and charged pion components feed energy into the electromagnetic component over many generations of interactions, $\sim 99\%$ of secondary particles at sea level are photons, electrons, positrons, and neutrinos. Their energy is mostly in the range 1 to 10 MeV and they transport 85% of the total energy. The remaining 1% of secondary particles are mainly muons with an average energy of 1 GeV and carrying about 10% of the total shower energy, but there are also a few pions with energies of a few GeV (about 4% of the total energy) and, in even smaller proportion, baryons. The lateral development of the shower is represented by its Molière radius, the distance within which 90% of the total energy of the shower is contained, which in air at Standard Temperature and Pressure (STP) is 70 m. However, the actual extension of the shower at ground level is of course much larger. As an example, at a distance of 1 km from the shower axis, the average densities of photons, electrons and muons are approximately 30, 2 and 1 per m$^2$, respectively.

One very useful property of air-showers is the depth of shower maximum $X_{\text{max}}$. It is measured from the top of the atmosphere as an amount of traversed matter in the units of g cm$^{-2}$ where the number of secondary particles reaches the maximum.

Showers initiated by heavier nuclei can be described by making use of a superposition principle. Development of showers initiated by a primary nucleus of mass number $A$ and energy $E$ can be modelled as a superposition of $A$ proton-initiated showers of energy $E/A$. Consequently, they are richer in muons and less penetrating than a nucleon with energy $E$. For example, an UHE iron-induced shower will reach its shower maximum roughly 100 g cm$^{-2}$ higher in the atmosphere than a proton one.

For a photon shower the proportion of muons will be even smaller. At the highest energies another physical process will have important consequences on photon shower development. This is the so-called Landau–Pomeranchuk–Migdal (LPM) effect [33,34] which describes the decrease of the photon/electron–nucleus cross-sections with energy and with the density of the medium with which they interact. Even in the upper atmosphere, the LPM effect becomes appreciable at energies in the $1 \times 10^{18}$ eV range so that it is possible for a photon of $1 \times 10^{20}$ eV to develop an air-shower very deep in the atmosphere, yielding less than $10^9$ particles at ground level.

The atmosphere is a nice, but a little complicated, calorimeter for measuring UHECR. Its main difficulty is that it is very troublesome to read out the signal. Up to now, only two main methods have been used:

![Figure 3. Schematic view of the development of air shower cascade.](image-url)
measuring the air-shower lateral distribution of particles by an array of particle detectors at ground level, and
- recording the air-shower development through the atmosphere from the faint nitrogen fluorescence light induced by secondary particles, which requires fast, high resolution and UV sensitive cameras.

A new technique was proposed recently which uses radar echoes from the column of ionised air produced by the shower [35]. Results of the first tests look quite promising. Details on each detection technique are given below.

4.2. Surface arrays

A ground array is a set of particle detectors, such as Cherenkov radiators or plastic scintillators, distributed as a more or less regular matrix over some surface. The main features of particle detectors are: fast response to EM radiation, good time resolution and sensitivity to muons. An example of such a detector is given in Figure 4.

An array of particle detectors can measure a two-dimensional spatial distribution and a time distribution of the arrival of the particles in the shower as it intersects the ground plane. The surface detectors are usually placed far apart from one another, sampling the shower far from its core. The array detectors count the number of secondary particles which cross them as a function of time. Therefore, they sample the non-absorbed part of the shower reaching the ground. The incident UHECR direction and energy are measured by assuming that the shower has an axial symmetry. This assumption is valid for not too large zenith angles (usually $\theta < 60^\circ$). At larger angles the low energy secondaries are deflected by the geomagnetic fields and the analysis becomes more delicate. The determination of the shower energy and the direction of the shower axis, i.e. the energy and direction of the primary cosmic ray, is obtained by simultaneously fitting the measured lateral distribution of EM particles and muons and their arrival times. In addition, the proportion of muons with regard to the EM component provides information about the identity of the primary cosmic ray.

The required size of the surface array is determined by the expected incident flux. The lower the flux, the larger must the array of surface detectors be.

Surface detector arrays have a nearly 100% duty cycle. One of the major disadvantages, however, is their inability to directly observe the development of the shower in the atmosphere. Thus, their energy measurement heavily depends on shower development simulations. Since interaction cross-sections at these energies are unknown, the results of simulations in turn heavily depend on the interaction models used.

4.3. Fluorescence detectors

Instead of sampling a shower with many detectors on a grid, fluorescence detectors follow the trajectory of an extensive air shower and measure the energy dissipated by shower particles in the atmosphere. Fluorescence detectors make use of the fact that the EM particles of the air shower cascade excite nitrogen molecules in the air which subsequently emit light in the ultraviolet part of the electromagnetic spectrum. The nitrogen fluorescence spectrum consists of several lines between 290 and 430 nm. The number of photons produced by a charged particle per unit track length, depends on pressure, temperature and humidity and yields approximately 3 to 4 photons per metre for MeV electrons in dry air at standard conditions. In addition to fluorescence photons, charged particles in the shower also produce a beam of Cherenkov light along the shower axis. In contrast to fluorescence light, Cherenkov light is strongly forward peaked. But some scattered Cherenkov light contaminates the fluorescence signal and needs to be accounted for in the reconstruction [36].

A fluorescence detector uses large mirrors to image the sky onto an array of photomultipliers. It can directly measure the longitudinal development of the shower. During dark nights, air showers will manifest themselves as light signals in a succession of photomultiplier tubes. The integral of the longitudinal profile is a calorimetric measure of the total shower energy that is nearly independent of the interaction models. Fluorescence detectors can also measure the position of shower axis and provide information on the
identity of the primary particle through the observation of the depth at which the shower maximum occurs ($X_{\text{max}}$).

Air fluorescence detectors are very powerful since they can observe air showers as far away as 30 to 40 km. Therefore, they have a very large instantaneous detection volume. They must be fast and able to record $10^8$ images per second. However, their operation requires dark, moonless nights with good atmospheric conditions, a requirement which typically limits their duty cycle to only about 10% compared to the essentially 100% duty cycle of the surface detector arrays. In addition, corrections have to be made for scattering and absorption of light by molecules and aerosols. Atmospheric effects not only attenuate the light signal, but they also create a non-negligible background component due to scattered Cherenkov light and multiply scattered fluorescence light from aerosols. Since the atmosphere is an integral part of the fluorescence detector, atmospheric conditions need to be monitored continuously during data taking using special devices like LIDAR scanners, cloud monitors, etc.

Ground array and fluorescence detection techniques are complementary and they supplement each other. That is why modern experiments like the Pierre Auger Observatory and the Telescope Array use both techniques simultaneously and operate in the so-called ‘hybrid mode’.

4.4. Radio detection

A more recent technique to detect air showers utilises the effect of radio frequency (RF) energy emission by charged particle showers. These radio pulses are produced by several mechanisms, though it is thought that from about 20 to 100 MHz, the dominant process can be described as coherent synchrotron emission by the electron and positron pairs propagating in the Earth’s magnetic field [37]. In the early 1960s RF pulses coincident with air showers were measured [38], but the promising results from surface arrays and fluorescence detectors caused this technique to be abandoned for some time. In the context of next generation digital telescopes more ambitious possibilities have been described (LOFAR [39]). The great potential of a large scale application has been reported by the LOPES project. They also confirmed that the emission is coherent and of geomagnetic origin, as expected by the geosynchrotron mechanism [40,41].

5. Experiments

Experimental research on UHECRs started almost 40 years ago with the Volcano Ranch experiment. Larger and more elaborate experimental devices were developed during the last four decades. Most of them detected cosmic rays with energies around or exceeding $1 \times 10^{20}$ eV. The corresponding detectors are briefly described below.

- **Volcano Ranch, New Mexico, USA** [1] was the first detector claiming to have detected an event with energy exceeding $10^{20}$ eV in February 1962. It was an array of 3 m$^2$ scintillator counters with a spacing of 900 m and a total area of about 8 km$^2$. The detector’s total exposure was estimated to be of the order of 60 km$^2$ sr year.

- **SUGAR array, Narrabri, New South Wales, Australia** [9–11] was the only giant array to have operated in the Southern Hemisphere. It contained 54 scintillation stations deployed over an area of 60 km$^2$. Unfortunately the spacing between the detectors, typically one mile, proved to be too large and, even in the events with the largest energies, the number of stations fired was small. Thus, the energy assignment was poor and the data have to be compared with those from other experiments with great care. The data are mainly useful because they form a unique set for arrival direction studies in the Southern sky.

- **Haverah Park, United Kingdom** [7,8] was an array of water Cherenkov tanks of various sizes and spacings covering an area of 12 km$^2$. The detector took data during almost 20 years from 1968 to 1987 with a total exposure of 270 km$^2$ sr year. It reported four events with energies around $10^{20}$ eV.

- **Yakutsk, Siberia, Russia** [14] was by far the most complex of the giant arrays at that time. It consisted of scintillator counters, muon detectors and Cherenkov tanks. This array began taking data in 1970 and was developed to cover an area of 20 km$^2$ in 1974.

- **Fly’s Eye, Utah, USA** [15] was the first successful air fluorescence shower detector and showed its power in energy resolution and in composition resolution. It consisted of two fluorescence telescopes located at different positions and offered the possibility to observe air showers either in mono (an air-shower detected only by one of the two telescopes) or stereo mode. Its total exposure is estimated at about 600 km$^2$ sr year in the mono mode and 170 km$^2$ sr year in the stereo mode. The Fly’s Eye detected the most energetic particle ever seen, with an approximate energy of $3.2 \times 10^{20}$ eV. Unfortunately, it was detected in the mono-mode, hence with relatively large errors on the measurements of the incident
direction and energy of approximately $6^\circ$ and $0.9 \times 10^{20}$ eV, respectively.

- **AGASA, Akeno, Japan** [12,13] was the largest operating ground array in the world before the Pierre Auger Observatory came into operation. It is composed of 111 scintillator counters with a surface of 2.2 m$^2$ and 27 muon counters. The spacing between counters is almost 1 km and the array spreads over an area of 100 km$^2$. AGASA has taken data since 1990, with a total exposure of 670 km$^2$ sr year. It reported the detection of 11 events with an energy exceeding $10^{20}$ eV.

- **HiRes detector, Utah, USA** [42] is a successor to the Fly’s Eye detector. It utilises the air fluorescence technique and consists of two sites separated by approximately 13 km. The optical systems at both sites consist of spherical mirrors of 3.8 m$^2$ area. The light collected by the mirrors is focused onto clusters of hexagonal PM tubes closely packed into 16 rows by 16 columns. Each tube views a 1 degree by 1 degree patch of the sky. The HiRes1 consists of 21 mirrors that view almost the full 180° azimuthal range from 3° to 17° above the horizon. The HiRes2 consists of 42 mirrors that view about 80% of the azimuthal range from 3° to 31° above the horizon. The electronics of HiRes2 detector is based upon 100 MHz FADCs. The PMT signals are therefore sampled every 100 ns. The trigger for the FADC is based upon digitised information. Timing of the two sites is synchronised by GPS.

6. The Pierre Auger Observatory

The present flagship in the study of UHECRs is the southern site of the Pierre Auger Observatory situated in the Argentinean pampa. It is the largest calorimeter for measuring UHECRs in the world with a volume exceeding 40,000 km$^3$ and one of the two running experiments which operates in hybrid mode, i.e. using a surface detector array and fluorescence detectors. R&D on radio detection is already going on and an upgrade with radio detectors is foreseen if the method proves to be adequate and efficient.

The Pierre Auger Observatory is an international effort of research groups from 18 countries, in total counting more than 450 scientists and technicians. In Figure 5 the final layout (neglecting small uncovered areas) of the southern site in the Province of Mendoza, Argentina, is shown. To bridge the gap between experimental results of different types of detectors, the Pierre Auger Observatory thus uses the two complementary methods of extended air-shower detection.

The **surface detector (SD)**, represented by dots in Figure 5, is an array of over 1600 water-Cherenkov detectors arranged on a triangular grid with 1500 m spacing, covering an area of over 3000 km$^2$. Each detector holds 12 t of highly purified water observed by three photomultiplier tubes (PMTs) measuring electrons, photons and muons of extensive air showers at ground level (see Figure 4).

The **fluorescence detector (FD)**, represented by blue dots and lines in Figure 5, consists of 24 optical telescopes overlooking the array. Each telescope covers 30° range in azimuth and 2° to 32° range in elevation. The telescopes are mounted in four fluorescence buildings situated at the array border. They can observe the longitudinal shower development by detecting the fluorescence and Cherenkov light produced along the shower trajectory in the atmosphere.

Around 10% of the data is taken in the so-called hybrid mode, reducing systematic uncertainties and enabling the study of cross-correlations between the two experimental techniques.

Figure 5. (a) Layout of the southern observatory in the Province of Mendoza, Argentina. Dots indicate the positions of 1600 Cherenkov water tanks of the surface detector. Positions of the four fluorescence detector sites are also indicated. See detailed explanation in the text. (b) Simulation of an air shower detection.
With stable data-taking starting in January 2004, the world’s largest dataset of UHECR observations has been collected over the last five years.

7. Selected results
In the following section a selection of results will be presented according to the personal preference of the author. According to his opinion, they represent a new insight into the UHECR mystery.

7.1. Energy spectrum
The methods used by the Pierre Auger Observatory to derive the UHECR energy spectrum are almost free of any assumptions on primary composition or hadronic interaction models. The hybrid design of the observatory allows us to combine the advantages of large SD aperture with the nearly calorimetric FD energy measurement.

The energy assignment to the SD events is done in two steps. For each event an energy-related parameter \( S_{1000} \) is established first as the estimate of the integrated signal on the ground at a distance of 1000 m from the shower axis, obtained from the lateral distribution fit of the signal. Simulations show that \( S_{1000} \) is almost proportional to primary energy and that the fluctuations in the lateral distribution are minimised for this kind of array geometry for distances around 1000 m from the shower core. Due to the larger attenuation of slanted showers the angular distribution of \( S_{1000} \) is not equal to what we would expect from the isotropic and uniform flux of cosmic rays. Assuming that the incoming cosmic rays are indeed isotropic and homogeneous, the departure of the angular distribution of \( S_{1000} \) from the isotropic prediction is with simple polynomial fit parametrised as the attenuation effect. With this polynomial, the attenuation effects are removed so that each shower parameter \( S_{1000} \) at zenith angle \( \theta \) is transformed into an equivalent parameter \( S_{38} \) at \( \theta = 38^\circ \). The angle of \( 38^\circ \) was chosen based on the fact that for the real showers the distribution in zenith angle exhibits a maximum close to the \( 38^\circ \) angle. With such a procedure, sometimes also called ‘constant intensity cut’, showers with different arrival directions are placed on a common footing, at least when the atmospheric attenuation effects are concerned. The second step is done with the \( S_{38} \) -to-energy conversion, calibrated from a subset of doubly reconstructed events, i.e. events that can be independently reconstructed by use of the FD or SD data only. The correlation curve of the respective energies is seen on Figure 6.

Since completion of the observatory in June 2008 the exposure is increasing each month by about 350 km\(^2\) sr year and currently amounts to 12,790 km\(^2\) sr year for the time period considered for this analysis. The systematic uncertainty of the energy cross-calibration is 7% at \( 10^{19} \) eV and increases to 15% above \( 10^{20} \) eV [43].

Due to the overall energy resolution of the surface detector data of about 20%, bin-to-bin migrations influence the reconstruction of the flux and spectral shape. To correct for this effect, a simple forward-folding approach was applied. It uses Monte Carlo simulations to determine the energy resolution of the surface detector and derive the bin-to-bin migration matrix. The matrix is then used to derive a flux parameterisation that matches the measured data after forward-folding. The ratio of this parameterisation to the folded flux gives a correction factor that is applied to the data. The correction is energy dependent and smaller than 20% over the full energy range.

The derived energy spectrum of the surface detector is shown in Figure 7 together with the number of events of the underlying raw distribution. Combining the systematic uncertainties of the exposure (3%) and of the forward folding assumptions (5%), the systematic uncertainties of the derived flux is 5.8%.

The Auger energy spectrum at energies above \( 10^{18} \) eV is derived by combining SD and FD measurements. The combination procedure utilises a maximum likelihood method which takes into account the systematic and statistical uncertainties of the two spectra. The systematic uncertainty of the combined flux is less
than 4%. As the surface detector data are calibrated with hybrid events, both spectra share the same systematic uncertainty for the energy assignment. The main contributions to this uncertainty are the absolute fluorescence yield (14%) and the absolute calibration of the fluorescence photodetectors (9.5%). By including a reconstruction uncertainty of about 10% and uncertainties of the atmospheric parameters, an overall systematic uncertainty of the energy scale of 22% has been estimated [43]. Details of the analysis can be found elsewhere [46].

The fractional difference of the combined energy spectrum with respect to an assumed flux proportional to $E^{-2.6}$ is shown in Figure 7. An abrupt change in the spectral index near $4 \times 10^{18}$ eV is observed, suggesting a change from galactic to extragalactic component. In addition, a suppression of the flux beyond about $3 \times 10^{19}$ eV is clearly indicating the GZK feature and indicating that possible UHECR sources might be in our cosmological neighbourhood.

From data shown in Figure 7(b) one can make a comparison between measured spectrum by HiRes and the P. Auger Collaboration. Taking into account the energy resolution and possible shift in energy scale, we can conclude that both measurements are consistent. Both experiments clearly observe the GZK feature and do not confirm the AGASA claim of a continuing spectrum beyond the GZK cutoff.

**7.2. Arrival directions**

An insight into the origin of UHECRs can be obtained by studying their arrival directions. Observations are influenced by galactic and extragalactic magnetic fields which deflect charged particles so that their arrival directions do not point back to their source. However, it is expected that as the energy of UHECRs increases, the correlation between the arrival directions and position of sources should increase, too.

Using data collected between 1 January 2004 and 31 August 2007, the Pierre Auger Observatory has reported [47,48] evidence of anisotropy in the arrival directions of UHECRs with energies exceeding $6 \times 10^{19}$ eV. The arrival directions were correlated with the positions of nearby Active Galactic Nuclei (AGN) from the twelfth edition of the catalogue of quasars and AGNs by Véron-Cetty and Véron [49] (VCV catalogue).

Recently, the Pierre Auger Collaboration reported on an updated analysis of correlation with AGN in the VCV catalogue by including data collected through 31 March 2009. The integrated exposure for this event selection amounts to 17,040 km$^2$ sr year ($\pm3\%$), nearly twice the exposure used in [47,48]. The analysis was the same as in [47,48], but performed on an enlarged data sample. Events observed prior to 27 May 2006 were excluded since this sample was used for the exploratory probability scan. Results are presented in Figure 8.

Figure 8(a) displays the Hammer–Aitoff projection of the arrival directions of cosmic rays with $E > 6 \times 10^{19}$ eV. The anisotropy is seen even by the naked eye and is confirmed by statistical tests. A sequential test rejects the isotropic hypothesis at the 99% significance level and with less than 5% chance of incorrectly accepting the null hypothesis.
The likelihood ratio test indicated a 99% significance level for the anisotropy of the arrival directions using the independent data reported in [47,48]. Subsequent data neither strengthen the case for anisotropy, nor do they contradict the earlier result. The departure from isotropy remains at the 1% level as measured by the cumulative binomial probability with 17 out of 44 events in correlation [50].

In Figure 8(b) is plotted the degree of correlation \( p_{\text{data}} \) with objects in the VCV catalogue as a function of the total number of time-ordered events observed since 27 May, 2006. For each new event the best estimate of \( p_{\text{data}} \) is \( k/N \) with \( k \) the number of events satisfying the correlation criteria out of a total of \( N \) satisfying the energy cut. The 1\( \sigma \) and 2\( \sigma \) uncertainties in this value are determined such that the area under the posterior distribution function is equal to 68% and 95%, respectively. The current estimate, with 17 out of 44 events correlating in the independent data, is \( p_{\text{data}} = 0.38 \pm 0.07 \). Events to the left of the dashed vertical line correspond to period from 27 May 2006 through 31 August 2007 and those to the right correspond to period from 1 September 2007 through 31 March 2009.

The VCV catalogue is not an unbiased statistical sample of corresponding astronomical objects, since it is neither homogeneous nor statistically complete. This is not an obstacle to demonstrate the existence of anisotropy if UHECR arrive preferentially close to the positions of nearby objects in this sample. The nature of the catalogue, however, limits the ability of the correlation method to identify the actual sources of UHECRs. The observed correlation identifies neither individual sources nor a specific class of astrophysical sites of origin. It provides clues to the extragalactic origin of the UHECR and suggests that the suppression of the flux in Figure 7 is due to interaction with the cosmic microwave background radiation. It is clear that more data are needed to learn more about possible sources. Nevertheless, the result exhibits evidence for the anisotropy of the UHECR arrival directions and/or of the possible astronomical sources.

### 7.3. Composition

The fluorescence detector of the Pierre Auger Observatory can be used to measure with good resolution the shower longitudinal profile and the depth at which the shower reaches its maximum size, \( X_{\text{max}} \). At a given energy, the average \( X_{\text{max}} \), denoted by \( \langle X_{\text{max}} \rangle \), and the dispersion or width of the \( X_{\text{max}} \) distribution, denoted by \( \text{RMS}(X_{\text{max}}) \), are both correlated with the cosmic ray mass composition [32,51–53]. Proton showers penetrate deeper into the atmosphere (larger values of \( X_{\text{max}} \)) and have wider \( X_{\text{max}} \) distributions than heavy nuclei. The mass composition interpretation of the measured mean and width of the \( X_{\text{max}} \) distribution depend on the assumed model of hadronic interactions. The problem is that at these high energies, the uncertainties in the predictions from the models are unknown because they are an extrapolation of the physics from lower energies.

We show in Figure 9 the latest result of the dependence of \( X_{\text{max}} \) on energy, the so-called elongation rate measured by the Pierre Auger Collaboration [59]. One can observe a trend in the mean \( X_{\text{max}} \) towards higher interaction altitudes in the atmosphere and similarly the fluctuations of \( X_{\text{max}} \) decrease almost to the resolution limit of the FD telescopes of about 20 g cm\(^{-2}\). Implicitly, the graphs suggest an interpretation in terms of UHECR composition becoming heavier or...
mixed with increased energy. However, we should not forget that interaction models used in the simulations do not cover all possible extrapolations of lower energy accelerator data. An unambiguous interpretation of the Pierre Auger Collaboration results would require additional hadronic interaction data from accelerators or information constraining particle masses from UHECR arrival directions.

7.4. Photon fraction

Photons can be produced during the UHECRs acceleration and propagation and most abundantly in exotic sources. A large fraction of detected UHECR photons would be a clear evidence for exotic sources scenarios [24].

Photon showers differ substantially from hadron induced ones. They penetrate 200 to 300 g cm$^{-2}$ deeper in the atmosphere, their signal rise-time and the curvature of their shower front are closely related to the depth of the shower maximum. The first observable can be used in the analysis of FD data which is statistically less significant due to the low duty cycle of FD detectors but is very clean. The second characteristic of photon showers is used for the analysis of SD data. No photon induced showers were found in the Pierre Auger Observatory data which resulted in the extraction of photon flux upper limits only. A compilation of current photon fraction limits together with model predictions is shown in Figure 10.

The Pierre Auger Collaboration results agree well with other experiments at the highest energies. In addition, they extend to the lowest part of the UHECR spectrum which was not explored by previous experiments. Present results already disfavour most of the models with exotic sources and are in agreement with GZK and anisotropy observations which favour conventional acceleration production of UHECRs.

As the Pierre Auger Observatory runs and adds more statistics, this analysis may either exclude the existence of UHECR photons or find them at a limited fraction of the total flux.

8. Future prospects

The southern site of the Pierre Auger Observatory will add about 7 × 10$^3$ km$^2$ sr each year in exposure to the southern sky with a total accumulation reaching about 10$^5$ km$^2$ sr year at the end of the decade. In the same time interval, the Telescope Array [72] with one fourth the area of the Auger southern site will add about 2 × 10$^4$ km$^2$ sr year to the northern sky exposure.
Taking into account the number of trans-GZK events observed by the Pierre Auger Observatory so far, an estimate of astronomically useful events that current observatories could detect by 2020 would be about 500 and progress will be limited by the lack of exposure to even the nearby sources.

To fully explore the features of UHECR, next generation observatories with full sky coverage and an order of magnitude increase in exposure need to be built in the future. Large aperture projects have already been proposed: the ground based northern site of the Pierre Auger Observatory [73] and space-based JEM-EUSO [74].

8.1. Northern site of the Pierre Auger Observatory

The Pierre Auger collaboration had foreseen the northern part of the observatory already in its original documents in order to assure the full sky coverage. Design of an enlarged northern site of the observatory is now ready and the search for funds has already begun.

The northern site of the Pierre Auger Observatory will use the well-proven detector components developed already for the southern site. It will focus on achieving higher statistics at energies above \(6 \times 10^{19}\) eV, where the GZK-effect makes it possible to study nearby sources without the isotropic background from the rest of the far universe. Thus, the surface detector can be a relatively sparse array with the largest conceivable instrumented area. As seen from Figure 11, the planned size of the surface array is gargantuan, covering an area of 20,000 km\(^2\) which is approximately the size of Slovenia, the smallest country participating in the project.

The array will be covered as much as possible by fluorescence telescopes to ensure the model independent energy calibration and accurate particle identification. These features enable, among other things, studies of particle physics at the energy frontier.

The site, chosen in 2005, is located in the south-east corner of the State of Colorado, USA. The average altitude is about 1300 m above sea level and the landscape is almost flat. It offers an exceptionally large area with the possibility of further extension eastward into the State of Kansas.

The surface detector array will consist of 4000 stations deployed on a rectangular pattern with a nominal detector spacing of 2300 m. Almost full coverage of the SD grid will be achieved with 39

Figure 11. (a) Site map of the Auger Northern Observatory. Each dot represents one water-Cherenkov tank. The proposed positions of the of fluorescence buildings are also shown together with the distant laser facilities. (b) Size of P. Auger Southern and planned Northern Observatory compared with the size of Slovenia.
fluorescence telescopes arranged in five locations, anticipating a usable viewing distance of 40 km. A peer-to-peer data communication system rather than a direct station-to-tower transmission will be used to guarantee a reliable data flow for stations located in shallow valleys. Technically, the construction of the northern site could begin in year 2011.

8.2. JEM-EUSO

The basic idea of space-borne experiments is to observe the fluorescence light of air showers from space. The Extreme Universe Space Observatory (EUSO) aims to reconstruct the three dimensional shower development from a series of shower images. A Phase-A study of EUSO under the European Space Agency had successfully finished in July 2004. Later, the project evolved as a mission attached to the Japanese Experiment Module/Exposure Facility (JEM) at the International Space Station (ISS). JEM-EUSO is now targeting the launch in 2013 in the framework of a second phase of the JEM/EF utilisation [74].

The main component of JEM-EUSO is a UV telescope mounted on the ISS (see Figure 12). The field of view of 60° from a 430 km orbiting altitude corresponds to the observation of a circular area of 250 km radius. Assuming 10% duty cycle, the effective geometric aperture would thus be $5 \times 10^4$ km$^2$ sr.

The optical system consists of a pair of double-sided Fresnel lenses with 2.5 m diameter. The angular resolution of the optics is about 0.1°. The curved focal surface has 2.5 m diameter and is covered by a mosaic of about 6000 multi-anode photomultipliers. The main instrument is assisted by atmospheric sounding devices like LIDARs and IR cameras that will provide real time atmosphere transparency measurements.

JEM-EUSO is a large aperture device, optimised for energies above $10^{20}$ eV. Since the arrival directions of cosmic particles will be determined with an accuracy better than a few degrees, it also has a potential of finding sources of UHECRs.

9. Conclusions

The experimental study of cosmic rays has a long and bright history. Many discoveries have been made in particle physics as well as in astrophysics. UHECR research started many decades ago. Although the highest energy events were measured already in the 1960s, more progress was impossible due to very low fluxes. Advances required extremely large experimental devices that became possible only in 1990s due to the new technologies, in particular in telecommunications.

Recent experimental data from new generation experiments, like the HiRes fluorescence observatory and the Pierre Auger Observatory operating in hybrid mode shed new light on decades-old enigma of the origin of UHECRs. Both collaborations have reported the existence of the GZK cut-off indicating that the UHECR sources might be in our cosmological neighbourhood and/or the cosmic accelerators are running out of power at extreme energies.

The measured gamma ray fractions of UHECRs are low, excluding most of the top-down scenarios. This conclusion is supported by anisotropy results from the Pierre Auger Observatory favouring the existence of astrophysical sources of UHECRs.

Many open questions remain, especially the chemical composition of UHECRs. Finding individual sources which are probably very faint although situated in the near Universe, is a tantalising problem which probably will be left for the next generation of experiments. A common requirement for all of the

Figure 12. Artist’s view of the JEM-EUSO telescope mounted on the ISS. Figure courtesy of JEM-EUSO Collaboration.

Figure 13. Exposures of UHECR observatories as a function of time. The JEM-EUSO project is a space born experiment on the ISS, whereas the other observatories are ground based. Figure courtesy of the Auger Collaboration.
open scientific questions concerning UHECRs is a large aperture, achievable either by building larger terrestrial observatories or by building space-born experiments.

Currently, two projects are in the mature design phase, namely the northern site of the Pierre Auger Observatory and the JEM-EUSO experiment. Both will be ready to start construction in a few years, if funded. Their contribution to the exposure can be seen in Figure 13. The northern site of the Pierre Auger Observatory, if built, can raise the total exposure almost two orders of magnitude, reaching $1 \times 10^6 \text{km}^2\text{sr}$ year at the end of the next decade, enabling a study of UHECR sources and properties in great detail, resulting in the solution of this decades-old enigma.

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Danilo Zavrtanik studied physics at the University of Ljubljana, Slovenia and obtained his Ph.D. in 1987. He became professor of Physics at the University of Ljubljana in 1991 and served from 1992 to 1996 as Director General and member of the Scientific Council of the Jožef Stefan Institute in Ljubljana. In 1998 he became President of the Nova Gorica Polytechnic and Head of their Laboratory for Astroparticle Physics. In 2006, Nova Gorica Polytechnic evolved into the University of Nova Gorica where he is serving as the President, and is currently chairing the Rectors’ Conference of Slovenian Universities. Although his administrative duties are stretched over a broad range of assignments, he still finds research as an inspiring and relaxing activity. His research interests are in experimental particle physics and lately astroparticle physics. He was holding various steering positions in OMICRON, CPLEAR and DELPHI experiments at CERN and is presently involved in the Pierre Auger Collaboration, chairing its Collaboration Board. He was awarded the National Award for Science in 2004 and in 2005 the ‘Order for service’ decoration of the President of the Republic of Slovenia.

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