Ultra high energy cosmic rays: present status and recent results

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Cosmic rays with energies above 10^{20} eV are the highest-energy particles ever observed in the Universe. Their flux is so small that up to now only about two dozen such particles have been detected by past and present observatories. Their nature, the location of their sources and the mechanisms by which they are produced or accelerated constitute still a mystery worth of investigating by gathering much higher statistical samples of such events. The Pierre Auger Observatory is a large-area hybrid detector that is under construction to study such ultra high energy cosmic rays. At present the southern site is near completion and it already constitutes the largest scientific observatory ever built to study cosmic rays. In this paper we describe the latest status of ultra high energy cosmic ray research with an emphasis on the Pierre Auger Observatory.

Keywords: Cosmic rays.

Los rayos cósmicos con energías de 10^{20} eV representan las partículas con mayor energía jamás observadas en el Universo. Su flujo es tan bajo que hasta ahora solo se han detectado unas dos docenas de estas partículas con observatorios pasados y presentes. Su naturaleza, la localización de sus fuentes, y los mecanismos por los que son producidas o aceleradas continúan siendo un misterio que vale la pena investigar obteniendo muestras estadísticas mucho mayores de dichos eventos. El Observatorio Pierre Auger es un detector híbrido de gran área que se encuentra actualmente en construcción y que se dedicará a la observación de rayos cósmico de alta energía. En este momento, el observatorio en el sur esta prácticamente terminado y ya constituye el mayor observatorio de rayos cósmicos jamás construido. En este artículo se describe el estado actual de la investigación de rayos cósmicos de ultra alta energía haciendo énfasis en el papel del observatorio Pierre Auger.

Descriptores: Rayos cósmicos.

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1. Introduction

Cosmic rays are particles that arrive constantly at the Earth from deep space imperceptibly to the human senses. Those of the lowest energies come from the Sun or other nearby stars. Cosmic rays of higher energies, up to 10^{14} eV come from supernova explosions or other violent phenomena in the galaxy. It is believed that those of the highest energies, more than 10^{20} eV, are produced in astrophysical cataclysms outside the Milky Way. Their flux has been repeatedly measured with increasing accuracy since Victor Hess discovered them in 1912, by several experiments over an energy range from 10^9 eV up to the so called ultra high energy cosmic rays (UHECRs) with energies above 10^{19} eV.

As shown in Fig. 1, their flux decreases steeply as their energies increase: from 200 particle m^{-1} sr^{-1} s^{-1} for low energies of around 10^9 eV, to a flux 30 orders of magnitude smaller for the highest energies detected so far of 10^{20} eV (equivalent to tens of Joules) with a measured flux around one particle km^{-1} sr^{-1} per century. They are the highest-energy particles ever observed in our Universe with energies over 100 million times greater than the maximum energies obtained with present man-made accelerators.

The first cosmic ray with energy greater than 10^{20} eV was detected in 1962 in an observatory called Volcano Ranch which used plastic scintillators to detect extensive air showers (EAS) of secondary particles produced by the interaction of primary cosmic-ray particles with nuclei of the Earth atmosphere. Since then, there have been over two dozen of such events detected by half a dozen observatories around the world using different detection techniques. For this reason the existence of UHECRs is a very well established scientific result. However, their identity, their production mechanism and the location of their sources are still a mystery worth of a systematic study with a large collection-area observatory capable of accumulating sufficient events.

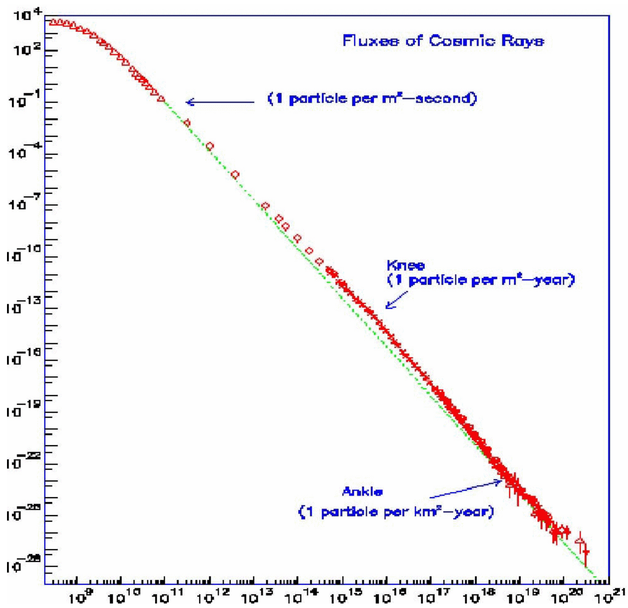

FIGURE 1. Energy spectrum of cosmic rays.

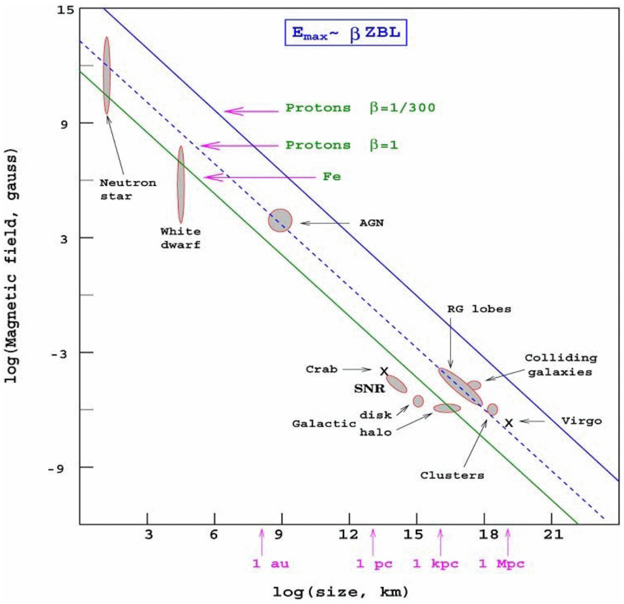

FIGURE 2. Magnetic field vs. size adapted from [5] of possible astrophysical sources capable of accelerating protons or iron nuclei up to energies of 10^{20} eV under the shock-wave acceleration model.

In the following sections we describe the presents status of theoretical models that have been proposed to explain different aspects of UHECRs, we also describe the different detection techniques and review the latest experimental results obtained by some of the observatories which have contributed most to enhance our knowledge of UHECRs, with an emphasis on the Pierre Auger Observatory. We also discuss briefly the characteristics of future observatories which are under design.

2. Acceleration Mechanism and Possible Sources

Soon after the discovery of the cosmic microwave background (CMB) in the 1960s, Greisen [1], and independently, Kuzmin and Zapsepin [2], realized that protons traveling with ultra high energies gradually lose their energy by interacting with these photons. This is due to the production of delta hadrons in the reaction of CMB photons with the traveling protons. The energy threshold for this proces is well defined at 5×10^{19} eV in the Earth frame. The ingredients needed for this calculation are well known: the CMB photon density of 400 cm^{-3} and the proton-gamma inelastic cross section of 6×10^{-28} cm^2.

This energy threshold is called the GZK cut-off. In turn, the existence of the GZK cut-off implies that protons arriving at the Earth with energies above 10^{20} eV should originate within distances not greater than around 100 Mpc. Other particles, such as ultra high energy photons or nuclei, also loose their energy by interactions with the background of infrared photons or by photo-pion disintegration, respectively. The assumption that the sources of cosmic rays are distributed uniformly over cosmological distances in the Universe, implies that, the energy spectrum of cosmic rays should have an abrupt cut-off for energies above 5×10^{19} eV, its existence is yet to be discovered observably.

On the other hand, if the galactic magnetic fields are what most specialists believe, i.e., on the average lower than a few micro Gauss on the galactic disk and decay exponentially away from it [3], and the extragalactic magnetic fields are lower than a few nano Gauss, then the deflections of UHECRs over distances lower than 100 Mpc should have typical values of around one degree. This very important conclusion means that the GKZ cut-off in the energy spectrum must be accompanied by anisotropies in the arrival directions of UHECRs, i.e., these directions must be correlated with the locations of nearby sources. Nevertheless, up to now there are no indications of any strong correlation between the arrival directions of the few UHECRs detected and the location of the more active galaxies located within a few hundred Mpc from the Earth.

UHECRs can be produced by two generically different ways [4]:

a) the so called bottom-up mechanism where acceleration of low energy particles occurs in the presence of shock waves and electromagnetic fields; and

b) the so called top-down mechanisms where massive particles disintegrate to produce the UHECRs observed; the required mother-particles must have masses much greater than 10^{20} eVc^{-2}; they have not been observed experimentally yet.

In relation to the first class of mechanisms, the candidate astrophysical objects require a product of their magnetic fields by their sizes proportional to the maximum energy at which they can accelerate particles [5], for acceleration outside the galaxy possible candidates are active galactic nuclei (AGN) and hot spots of radio galaxies lobes, see Fig. 2. In both cases, extremely violent astrophysical processes occur that possibly involve massive black holes. Other possibility is that free magnetic monopoles, whose existence has not been experimentally confirmed either, be accelerated in galactic or extra-galactic magnetic fields.

In relation to the second class of mechanisms, super massive particles and the so called topological defects might have been left as relics from the violent creation of the Universe [6]. The energy scale typically associated to these objects is the scale of the theories of Grand Unification, with particle masses of the order of 10^{24} eV; these particles could easily disintegrate giving rise to UHECRs with energies around or bigger than 10^{20} eV. Isotropic UHECRs could also result from cosmic strings [7].

Nevertheless, until now all the theoretical possibilities conceived to produce UHECRs have difficulties, i.e., there is not a single model that might be considered as the obvious candidate to explain the existence and measured properties of UHECRs. Therefore, it is crucial to measure accurately the energy spectrum, arrival direction and identity of UHECRs with a full sky coverage, if one wants to to be able to discard alternative models.

3. Past and present Observatories

The first observatories built to study UHECRs such as Volcano Ranch in the USA, Haverah Park in the UK [8], and Yakutsk in the USSR [9], were designed before the 1966 GZK cut-off prediction. In spite of their relatively small collection areas, of around 10 km^2, they were operated over sufficiently long periods of time and eventually led to the unambiguous conclusion that cosmic rays with energies above 10^{20} eV, *i.e.*, well above the GZK cut-off, exist and are not an artifact of the instrument used. They also obtained the first accurate measurements of the rate of cosmic rays above 10^{19} eV. More recent observatories, such as HiRes in the USA, with an energy-dependent aperture of around 3-7$\times 10^3$ km^3 sr, and AGASA in Japan, with a collection area of 100 km^2, increased the number of cosmic rays detected with energies above 10^{19} eV in an important way to the level where the GZK cut-off and anisotropies could be studied.

However, the small flux of UHECRs and the difficulty in controlling the different systematics involved in the energy measurements, have led to conflicting conclusions reported by AGASA [10] and HiRes [11] over the last half decade. This situation led, in the early 1990s, to the necessity of building a much larger observatory, with a better control of the energy-measurement systematics, to measure the spectrum around the GZK cut-off and to establish unambiguously the existence, or in-existence, of correlations of the arrival directions of UHECRs with the directions of known astrophysical objects. This was the beginning of the Pierre Auger Collaboration which at the moment consists of around 400 scientists from 65 institutions in 16 countries. The participating countries from LA are Argentina, Bolivia, Brazil and Mexico.

The design stage of the Pierre Auger Observatory began in 1995 and the construction of the southern site began in March 1999 in the province of Mendoza in Argentina. The northern site is currently under planning and it will be constructed in the the state of Colorado in the USA. The two sites are necessary to provide a full sky coverage.

4. Detection techniques

Ultra high energy cosmic rays are detected indirectly by studying the extensive air showers (EAS) of secondary particles produced by the interaction of primary cosmic rays with nuclei of nitrogen and oxygen of the Earth atmosphere at tens of kilometers above sea level. A first detection technique, pioneered by Fly´s Eye [12] consists of using ground telescopes to collect the fluorescence light produced by the Coulomb interaction of the secondary charged particles with the nitrogen molecules of the atmosphere. This technique has turned out to be very successful, even though it can be applied only at clear and moon-less nights.

A second technique consists on the direct sampling of the shower front as it arrives at the ground using particle detectors scattered over large areas. The Akeno Giant Air Shower Array (AGASA) [13] which operated in Japan until January 2004, used this method by sampling over a total area of 100 km^2 with plastic scintillator ground stations.

Over the past years AGASA and HiRes have reported measurements of the energy spectrum of UHECRs which disagree near the GZK cut-off. This is a consequence of the systematic errors on their energy measurement by as much as 20%. This errors make difficult to accurately measure the number of events with energies beyond the GZK cut-off.

The Pierre Auger Observatory [14] was designed to possess 3000 km^2 of detection area, i.e., 30 times greater than AGASA's and 10 times bigger than HiRes's. The Auger Observatory uses both methods of detection to obtain a high precision in the determination of arrival directions and the energies of cosmic rays. It has the potential to solve the present observational controversy once and for all.

In addition, the Pierre Auger Observatory will allow us to know what particles are involved. This is because it was designed to perform a much better statistical classification of the primary cosmic ray particle. This is based on the measurement of the depth at which a maximum occurs in the particle density along the longitudinal development of the extensive air shower (X_{max}), done with the fluorescence telescopes, and independent measurements of the muon contents of the EAS, measured with the surface detectors. The reason behind the use of these variables is that heavy nuclei have smaller X_{max} than protons of the same energy. Likewise, gamma rays have lower muon/EM ratios compared to protons; in turn protons have lower values of muon/EM than heavy nuclei.

In addition, the Pierre Auger Observatory has an increased capacity, with respect to previous observatories, to detect inclined EAS. This capacity makes the Auger Observatory an excellent instrument for detecting neutrino-induced EAS for the first time.

5. Description of the Pierre Auger observatory

The complete observatory will consist of two sites, one in Argentina and the other in the USA. At present the construction of the southern site in Argentina is 70% completed, see Fig. 3, converting it in the biggest instrument ever constructed to study cosmic rays. In fact, as we will mention later in more detail, many experimental results have been already obtained and reported [15].

The southern site is specially important because it is exploring a part of the sky that had not been explored with this type of instruments, with a preferential observation of the galactic center, including potential sources that cannot be seen from the northern hemisphere. The plan is to finish the southern site by the end of 2006.

The southern Pierre Auger Observatory will consist of a gigantic array of 1600 ground detector stations and 4 fluorescence eyes, consisting of 6 telescopes each, located on the border of the ground detector array. The ground detectors measure the lateral and temporary distribution of particles of the EAS at ground level, whereas the fluorescence detectors measure the longitudinal development of the EAS in the atmosphere over the surface array. At completion, the detector stations of the ground array will be distributed in a triangular grid with a 1.5 km spacing over an area of 3000 km^2.

Each one of the detector stations consists of a cylindrical tank made of polyethylene of 3.6 m diameter and 1.65 m height. The tank is filled with 12 ton of filtered water up to a height of 1.2 m. The inner surface of each of these tanks contains a bag made of tyvek, a material that reflects light in a highly diffuse way. The charged particles that arrive at the ground stations produce Cherenkov light when they cross the water volume, this light is detected by means of three 9 inch photo-multipliers that overlook the water volume from the top of the water surface.

The ground stations operate with solar power and communicate with a central station using radio signals. The arrival direction of primary cosmic rays is obtained through the precise measurement of the arrival time at each of the detector stations of the particles from the front of the EAS; this time is accurately measured by receiver units synchronized continually with the global positioning satellite system. These units are mounted on the top of each station. The signal from these stations is interpolated at a distance of 1000 m from the shower core; this interpolated signal has been found to be the best energy estimator for incident zenithal angles $< 60°$.

The fluorescence detectors consist of four eyes, see Fig. 3, located on the periphery of the surface array; in turn, each eye consists of 6 fluorescence telescopes. Each telescope consists of a mirror of 3.4 m of curvature radius which focuses UV light into a set of 440 photomultipliers. The field of view of each telescope is $30°$ in azimuthal angle by $30°$ in zenithal angle. Figure 4 shows the geometrical parameters involved in the detection of an EAS by a fluorescence eye. The systematic uncertainties associated to the energy measurement of primary cosmic rays with the fluorescence detectors are as follows: 5% in light collection; 12% in detector calibration; 2% in geometrical reconstruction; 10% in aerosol levels in the atmosphere; 5% in light absorption by clouds; 3% in the correction for missing energy and 15% in the yield of fluorescence light by electrons. These contributions add up to a total systematic error $< 25\%$.

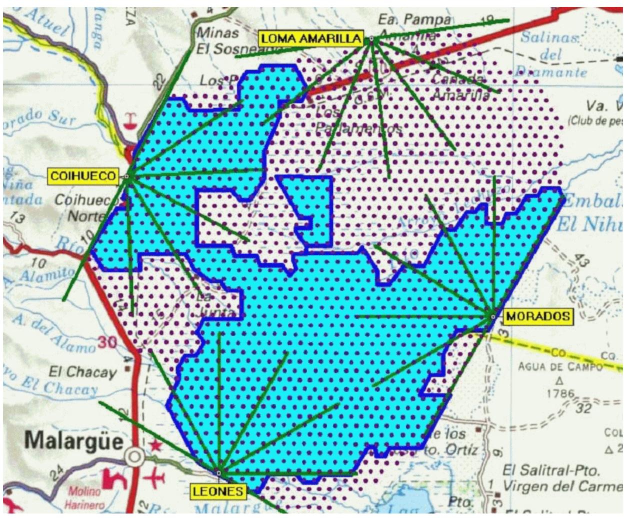

FIGURE 3. Status of construction of the southern site of the Auger Observatory by early 2006. More than 1000 surface stations and three fluorescence eyes are fully operational. The Loma Amarilla eye is under construction.

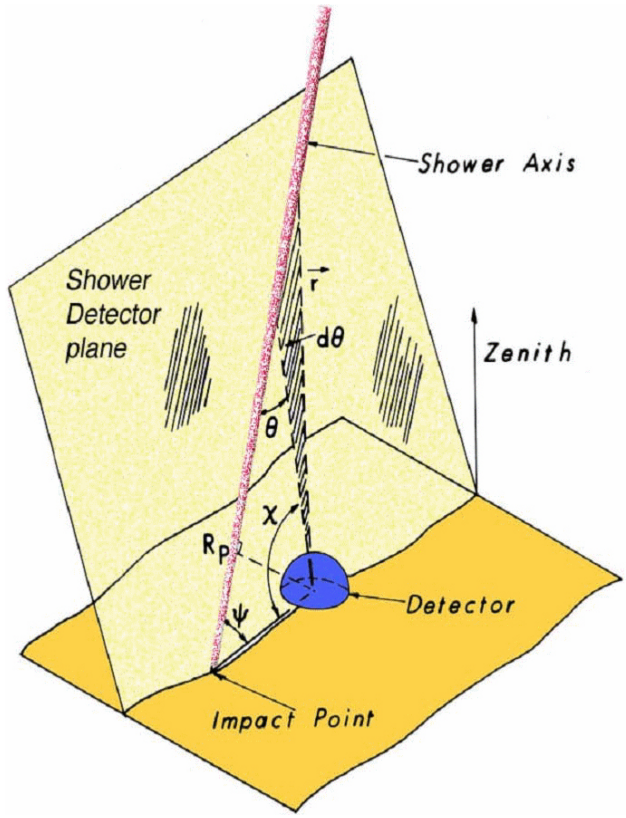

FIGURE 4. Geometrical parameters related to the detection of an extensive air shower with the fluorescence detectors. The shower axis is determined by a fit of the arrival times of the signals from the fluorescence eye to the EAS trajectory.

The southern site started operation on January 2004. By June 2005, the integrated exposure was 1750 km^2 sr year, *i.e.*, already bigger than the total integrated exposure that AGASA achieved during its operation. Out of the total number of events that the Observatory has detected, 10% are hybrid events, *i.e.*, detected simultaneously by the fluorescence and the ground station systems as shown schematically in Fig. 5. The design aperture of the southern site observatory is 7400 km^2 sr.

At present, May, 2006, there are more than 1000 surface detectors and 18 fluorescence telescopes which are fully operational. It is important to emphasize that the hybrid nature of the Auger Observatory allows, for the first time, the possibility to perform energy measurements of UHECRs in a way which is independent of Monte Carlo simulations. On the

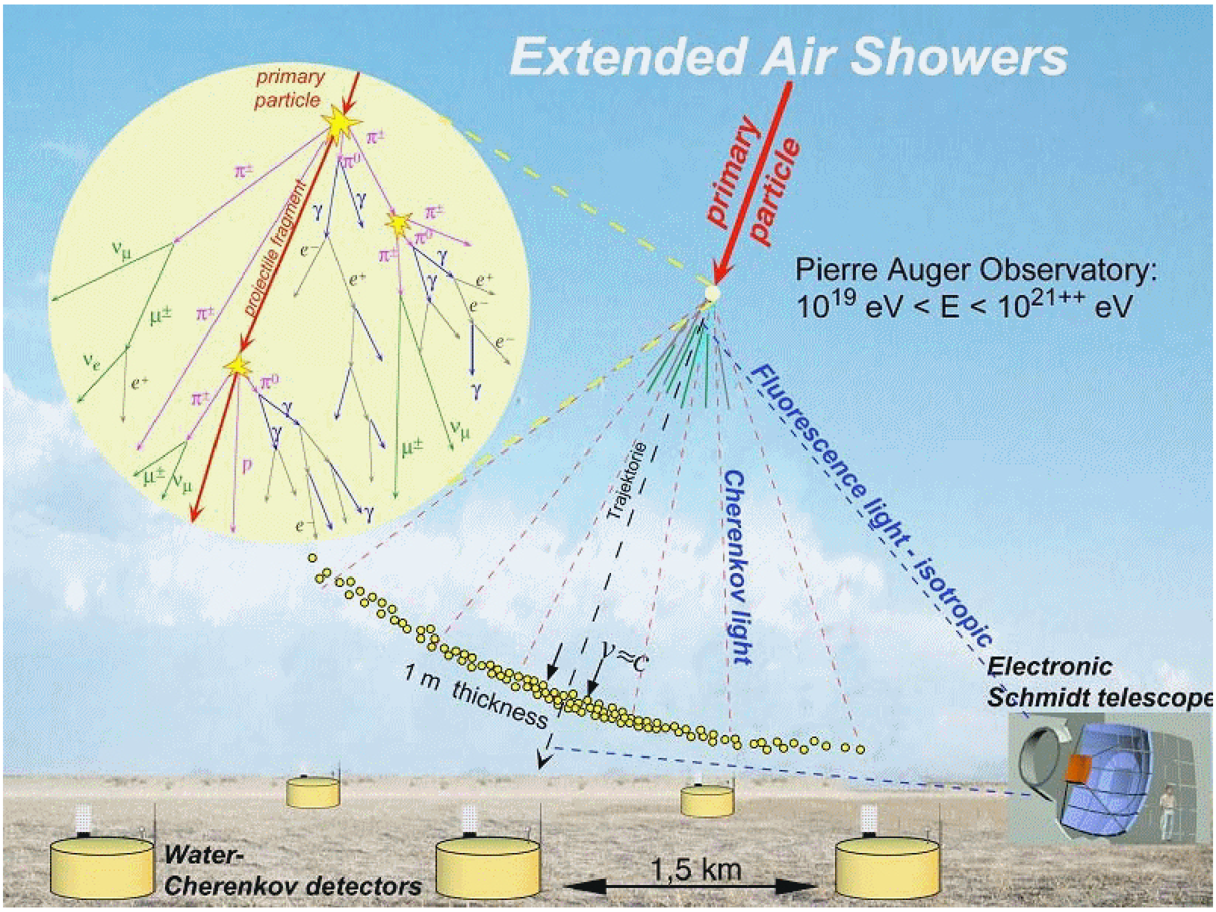

FIGURE 5. Artist's view of the detection of an extensive air shower in hybrid mode by the Auger Observatory.

other hand, the northern site of the Auger Observatory will be constructed in the state of Colorado, USA, initiating in 2007 and finishing in 2009.

6. Future Projects

There are a number of projects under planning or under R&D with the goal to detect UHECRs with a larger aperture. They main goal is to collect the fluorescence light produced by the particles from the EAS as they travel through the Earth atmosphere. The main innovation is that they will use one or more fluorescence telescopes located on a satellite. In this way the aperture of the instrument is greatly increased. Two such projects are TUS [16] and EUSO [17].

These projects expect event rates of the order of > 3000 year^{-1} with energies beyond the GZK cut-off. In particular, they expect > 700 year^{-1} events with energies $> 10^{20}$ eV. This represents an increase in aperture by a factor > 10 with respect to the aperture of the Auger Observatory. The main problem faced by these projects is the lower signal/noise and the much more difficult control of the systematic errors related to the larger path length of the UV-light emitted by the EAS in the Earth atmosphere. They, nevertheless, constitute one of the the most promising strategies to study UHECRs with energies well above the GZK cut-off in the future.

7. Recent Results

The following scientific results have been obtained with data from the Auger Observatory obtained from January 2004 to May 2005. The results described below were presented at the 29th. International Cosmic Ray Conference held in Pune, India, in August, 2005; they were based on a data sample of 180,000 events with $E > 10^{18}$ eV and $\theta < 60°$ after quality cuts, 10% of which were hybrid events [18].

7.1. Anisotropy Studies Around the Galactic Center

A search for excesses of events near the direction of the galactic center has been systematically performed in several energy ranges around energies of 10^{18} using data from the surface detector and also hybrid events [19]. The result is that no significant excess has been found. Likewise, searches for correlations of arrival directions with the galactic and the super-galactic planes at energies in the range 1-5$\times 10^{18}$ eV and $E > 5\times 10^{18}$ eV have found no significant excess. In this region the statistics accumulated by the Observatory is already larger than that of any previous experiment. These results do not support the excesses reported previously by the AGASA [20] and SUGAR [21] observatories.

7.2. Upper Limit on the Primary Photon Fraction

Based on observations of the depth of shower maximum, X_{max}, performed with the hybrid detector, an upper limit on the cosmic-ray photon fraction of 26% (at 95% confidence level) was derived for primary energies above 10^{19} eV. Additional observables recorded with the surface detector array, available for a sub-set of the data sample, support the conclusion that a photon origin of the observed events is not favored [22].

7.3. Angular Resolution

The angular resolution of the Auger Observatory has been determined experimentally for both classes of events: those detected in hybrid mode and those detected only by the surface detectors. The angular resolution for hybrid events is about $0.6°$, while the surface detector angular resolution is better than $2.2°$ for 3-fold events ($E < 4$ EeV), better than $1.7°$ for 4-folds events ($3 < E < 10$ EeV) and better than $1.4°$ for higher multiplicity ($E > 8$ EeV) [23].

8. Conclusions

Despite the fact that cosmic rays were discovered almost a century ago, the nature, origin and the mechanisms by which ultra high energy cosmic rays are produced or accelerated is still a mystery in astrophysics. Until now all the theoretical possibilities conceived to produce UHECRs have difficulties; it is, therefore, crucial to collect high statistics samples of measured UHECRs to determine their energy spectrum, arrival direction and identity with enough accuracy to discard alternative models.

The first observatories built to study UHECRs had relatively small collection areas. More recent and bigger observatories, such as HiRes in the USA and AGASA in Japan, have studied UHECRs in greater detail, however, the small flux of cosmic rays at the highest energies, and the difficulty in controlling the different systematics involved in their energy measurements, have led to conflicting conclusions reported by AGASA and HiRes over the last half decade. This situation led to the necessity of building the Pierre Auger Observatory which is not only a much larger observatory, but possesses a much better control of the energy-measurement systematics.

The primary goal of the Pierre Auger Observatory is to detect a high enough number of UHECRs to answer the three following questions:

i) is there a GZK cut-off in their energy spectrum?;
ii) what is their chemical composition? and
iii) where do they come from?

For this purpose, the observatory was designed in the 1990s to consist of two sites, one in the southern and the other in the northern hemisphere. The construction of the southern site of the Pierre Auger Observatory began in March, 1999, in the Province of Mendoza in Argentina. Since October 2003 it is the largest observatory ever built in the world to study cosmic rays. At this time, the Pierre Auger Observatory is studying cosmic rays with unprecedented detail and accuracy, surpassing by much the capacity of detection of previous observatories.

The southern site started its data-taking period in January 2004 and up to now it consists of around 70% of the 1600 surface stations distributed over an area of 3000 km^2 and 3 out of the 4 fluorescence eyes (with a total of 18 telescopes fully operational). It has already detected hundreds of thousands of cosmic rays with energies greater than 10^{19} eV, these events include 10% detected in hybrid mode, i.e., detected simultaneously with the surface and the fluorescence detectors. The surface detector array has shown its potential in the period from January 2004 to June 2005, achieving a total exposure of 1750 km^2 sr yr. It will gain one order of magnitude in integrated exposure by the end of 2006. In order to complete the observatory with the designed full-sky coverage, the construction of the northern site will begin in 2007 and will finalize in 2009.

The Pierre Auger Observatory has been in operation for more than two years and has shown very stable behavior. Up to June 2005, more than 180 000 events were recorded with an average rate of about 0.9 per surface station per day. Once the array is completed, a rate of about 1500 physics events per day is expected. A significant number of very horizontal events are detected, offering a novel view of EAS and opening the possibility to detect neutrino-initiated EAS. For events with energies above 10^{19} eV, the reconstruction accuracy is around $1.4°$ for direction [23] and around 10% for the signal at 1000m from the core, which is used as the surface energy estimator [24]. For a more complete discussion on the systematic errors on the energy determination refer to [25].

The lifetime of the Auger Observatory will be around 20 years. During this time it is hoped that it will gradually discover the sources of EHECRs; the Observatory also has the potential to discover neutrino-initiated extensive air showers. Likewise, the Observatory has the potential to lead to yet unexpected discoveries in astrophysics as it has happened in the past when new instruments have been used to explore our Universe.

Two projects currently in the R&D phase, TUS and EUSO, aim at detecting UHECRs with even larger apertures compared to the Auger Observatory´s. Their innovative instruments will collect the fluorescence light produced by the particles from the EAS as they travel through the Earth atmosphere by using one or more fluorescence telescopes located on a satellite.

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