Ultra High Energy Cosmic Rays and the Pierre Auger Project

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ABSTRACT: Unexpected events of ultra high energy cosmic rays have prompted the design and construction of the Pierre Auger Observatory. The motivations for and the structure of the observatory are briefly described.

1. Introduction

In its beginning, cosmic ray physics led to several key discoveries such as the discovery of the positron [1] (the first example of antimatter), the muon [2] (the first lepton different from the electron), the pion [3] (the particle predicted by H. Yukawa as responsible of the nuclear forces) and some *strange* particles [4] (later identified as kaones and Λ^0). The study of low energy cosmic rays made important contributions to our understanding of how the sun works and to the understanding of astrophysical acceleration mechanisms. Later on, particle accelerators took the leadership in the discoveries and in the study of the specific properties of elementary particles. This change was mainly motivated by the developments in acceleration technologies and to the possibility of producing intense and collimated beams. Nevertheless, at the present time one can say that the energies that will be reached in the terrestrial accelerators, will not go much beyond what is currently obtained. Cosmic ray physics, on the other hand, opens a window to physics where no other approach is viable. In particular cosmic rays may have energy much in excess of what is reachable in present and planed terrestrial accelerators.

In Mexico, cosmic ray physics was developed and reached its apogee during the 40's and 50's with the work of Manuel Sandoval Vallarta. This line of research did not remain as a top-priority for the reasons exposed in the previous paragraph. In the last few years, however, with the worldwide interest in ultra high energy cosmic ray physics, the area has reborn with a great boost with the leadership of high energy physicists, mainly.

The Mexican group consist of about 20 researchers and engineers participating in the project from four Mexican institutions: the Universidad de Puebla (BUAP), Centro de Investigacion y de Estudios Avanzados (CINVESTAV), the Universidad Michoacana (UMSNH) and the Universidad Nacional (UNAM).

2. An enigma

Cosmic rays are particles that come from extraterrestrial space. The amount of cosmic rays arriving to the top of the atmosphere quickly diminishes in function of its energy. For energies below 5×10^{19} eV one could say [5, 6] that the current physical theories successfully describe the decreasing rate versus energy in particle flux. However, beyond that energy the number of observed cosmic rays is considerably larger than the theoretical prediction [5]. The limit imposed by the theory arises from the following: the interstellar medium is filled by a tenuous and homogeneous radiation, the cosmic microwave background radiation, a relic of the Big Bang explosion whereupon the Universe was born. When the particles travel through the Universe, they

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Experiment	*Number of events*	*Year*
Volcano Ranch [8]	1	1962
Haverah Park [9]	4	1970 - 1980
Yakutsk [10]	1	1989
Fly's Eye [11]	1	1991
HiRes [12]	7	Active

Table 1: Events with energies higher than 10^{20} eV observed by several experiments

dissipate energy as a result of their interactions with this background radiation. At energies higher than 5×10^{19} eV the energy loss per distance unit is much higher, since at those energies the pion photoproduction plays an important role that causes a faster energy loss for the primary ray. As a consequence, there must be a limit on the energy which a particle arriving to the earth may have. The analysis indicates that this limit, called the Greisen-Zatsepin-Kuz'min (GZK) cut-off [7], is close to 5×10^{19} eV. This implies that a particle with very high energy will have a short mean free path. Therefore, particles arriving to the earth from distant astrophysical objects cannot have energies higher than the GZK cut-off. Some observed events, however, have overpassed this threshold (Tables 1 and 2)

These, isolated, but experimentally well established events, indicate a sudden and unexpected increase of the cosmic ray flux above 5×10^{19} eV, which in turn indicates the presence of a new ingredient not yet considered by the current theories that describe cosmic rays.

3. The ultra high energy events

Since the flux of ultra high energy cosmic rays arriving to the Earth is extremely low (1 particle /km^2 /century) at energies around 10^{20} eV, gigantic observatories are needed in order to acquire a significant number of these events in a reasonable time. From 1962 to May of 2000, considering all detectors installed around the world, 22 events have been obserbeed with energy $\geq 10^{20}$ eV, as shown in Tables 1 and 2. This number of events includes 7 HiRes preliminary ones. The analysis of the arrival direction of the AGASA events indicates no evident links to possible astrophysical sources, such as active galactic nuclei. While no significant large-scale anisotropy is found on the celestial sphere, some interesting clusters of cosmic rays are observed. Above 4×10^{19} ev, there are one triplet and three doublets within a separation of $2^\circ.5$ [14].

4. What do ultra high energy cosmic rays indicate?

The observation of cosmic rays with energies above the GZK cut-off suggests the existence of exotic sources. Some of these sources could be quasi-stable neutral massive particles, supersymmetric neutral matter, or topological defects that were formed in the early Universe [5]. The very existence of this ultra high energy cosmic rays could also evidence some other yet unknown phenomena, as for instance the violation of Lorentz invariance. An analysis with enough statistics of the spectrum of these ultra high energy cosmic rays will be able to set the starting point for the construction of a totally new theory of the subatomic world, more general than the Standard Model of elementary particles.

5. The Pierre Auger Observatory

The Pierre Auger Observatory will allow us to understand the origin and nature of the ultra high energy cosmic rays (those with energies higher than 5×10^{19} eV), one of the major mysteries of modern astrophysics. The Observatory will be the only one which, in the range of the highest detected energies, will have the capacity to acquire a statistically significant sample of these kind of events within a reasonable time. This in turn will allow us, among other things:

- To densely cover with data the cosmic rays spectrum at energies above 10^{19} eV.

Date	*Energy* $\times 10^{20}$ *eV*	*Elevation*	*Declination*
1993 01 12	1.01	08h 17m	16.8°
1993 12 03	2.13	01h 15m	21.1°
1994 07 06	1.34	18h 45m	48.3°
1996 01 11	1.44	16h 06m	23.0°
1996 10 22	1.05	19h 54m	18.7°
1997 03 30	1.50	19h 38m	-5.8°
1998 06 12	1.20	23h 16m	12.3°
1999 09 22	1.04	23h 03m	33.9°

Table 2: Events with energies higher than 10^{20} eV observed by the AGASA experiment [13]

- To determine with high precision (higher than in the previous scarce experimental data) the energy of primary particles with energies above 10^{19} eV (Table 3). This will be possible thanks to the hybrid nature of the observatory, which is described below.

	Surface Array	Hybrid Mode
At 100 EeV	15%	10%
At 10 Eev	30%	20%

Table 3: Energy resolution for the primary ray operating with the surface array only and in hybrid mode. 1 EeV = 10^{18} eV.

- To determine the arrival direction of the primary ray with an angular precision of 0.2 to 0.35 degrees (Table 4). This measurement will possibly allow one to make charged particle astronomy.

	Surface Array	Hybrid Mode
At 100 EeV	1°	0.20°
At 10 Eev	2°	0.35°

Table 4: Angular resolution for the incidence direction of the primary ray operating with the surface array only and in hybrid mode.

- To identify the nature of the particle that gives origin to the atmospheric shower distinguishing among showers initiated by protons, photons and heavy nuclei. The Pierre Auger Observatory will also have the ability of detecting horizontal showers initiated by neutrinos.

- The capability of measuring with high precision both the energy and the arrival direction, as well as the *chemical* composition of the ultra high energy cosmic rays, will allow us to study the Universe in a yet unexplored region of the spectrum, this would have important consequences in astrophysics and in the theory of elementary particles and their interactions.

5.1 Location

The optimal latitudes for the observatory, so that it can fulfill the goals for which it was designed, are in two narrow strips, one in the Northern hemisphere and another one in the Southern hemisphere. The strip of the north hardly touches the Northern border of Mexico and extends until a parallel that goes through the north of the State of Utah. The strip of the south is in a symmetrical position on the opposite side of the equator. The necessity of establishing the observatory in these zones and other technical requirements, including considerations such as the existing infrastructure, led the International Collaboration of the experiment to decide that the Pierre Auger Observatory[1] should consist of two gigantic facilities located one in the Southern hemisphere, in Malargüe, Argentina, and another one in the Northern hemisphere, in Utah, U.S.A.

5.2 The design

Each observatory will be hybrid, this means that in each one there will be an array of Cherenkov detectors (surface array) to register at ground

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[1] For information on the project see the web-page: http://www-lpnhep.in2p3.fr/auger/welcome.html.

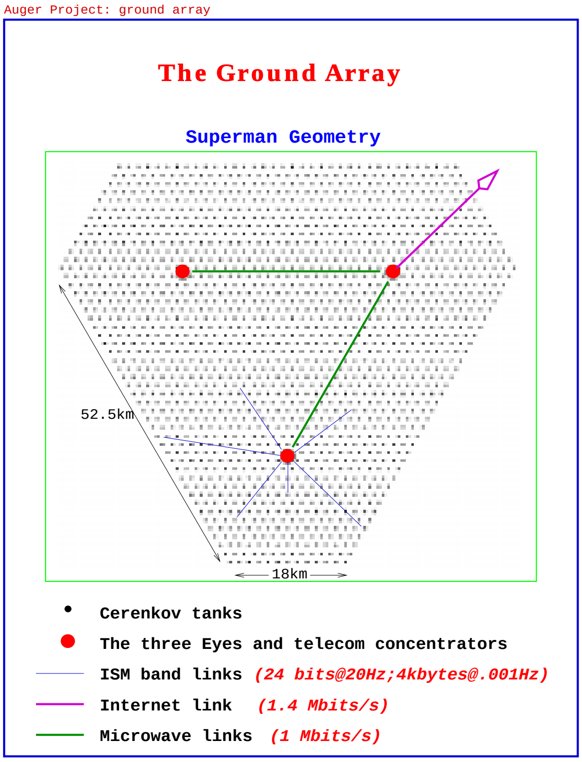

Figure 1: General layout for the distribution of detectors in a site.

level the showers of secondary particles generated as a consequence of the arrival of a primary ray to the atmosphere, but also, each facility will have a system of fluorescence detectors (four of these in the Southern site and three in the Northern one). The surface array will be a network of 1600 Cherenkov detectors separated 1.5 km from each other and distributed as it is depicted in Figure 1, where the location of three fluorescence detectors is indicated. The Cherenkov detectors will detect directly the charged secondary particles, whereas the fluorescence detectors will be sensible to the light emitted by atmospheric nitrogen molecules as a result of being excited by the particles of the shower.

Each Cherenkov detector uses a plastic tank of 12 m^3 filled with water. In water the more energetic secondary particles will emit Cherenkov radiation which will be caught and transformed into an electric pulse by three photomultiplier tubes located on the top of the tank. The signal of these photomultipliers will be processed by fast electronics located at each tank. This electronics will serve to digitalize the signals of the phototubes, adding *time stamps* (label with the arrival time), and sending signals to a central station where the signals of the fluorescence detectors will also be collected.

The fundamental part of each fluorescence detector is an optical detection system which covers a region of $360° \times 30°$ on the sky. This system is formed by 12 telescopes, each one of which covers a field of $30° \times 30°$. Each telescope consists of a Schmidt camera with a corrector ring at the stop plane, a primary mirror of 3.6 m of diameter possibly segmented up to a maximum of 36 segments and a diaphragm of 2.2 m of diameter. The ultraviolet radiation produced by the showers will be detected by a mosaic of 900 photomultiplier tubes placed at the focal surface of each telescope.

The simulation of the atmospheric showers generated by the primary cosmic ray, as well as that of the detectors and their response to the fluorescence and Cherenkov light produced by these particles, is fundamental to anticipate the performance of the detectors, and for adjusting the parameters associated with the longitudinal and lateral distribution of each atmospheric shower. The results have indicated that the designed observatory will fulfill its function for the determination of energy, direction and chemical composition of the primary cosmic rays, within the above mentioned accuracy.

5.3 Schedule

The construction of the Southern Observatory began in March of 1999. It will be completed by the end of 2003, although it is expected to start obtaining data earlier in 2002. The construction of the Northern Observatory will begin in 2003 and will end in 2005. The first stage in the construction of the Southern Observatory is called *Engineering Array.* This array includes two fluorescence detectors and 40 Cherenkov detectors, as well as the communication network and the data acquisition system which are needed for the autonomous operation of the system. The acquisition of the first data will start with the Engineering Array. The Engineering Array will also serve to improve the design of the rest of the observatory.

6. Conclusions

The Pierre Auger Observatory is well under construction and cosmic ray physics is about to receive a great impulse with large consequences for astrophysics and elementary particle physics.

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