Cosmic Accelerators and Terrestrial Detectors

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We review the status of ultrahigh energy cosmic rays studies, discussing the mechanisms for their production and propagation through space. We look into the strategy to measure those events and describe a new observatory, which is in construction, to observe those particles, the Pierre Auger Observatory.

I Introduction

The existence of cosmic rays with energies above 10^{20} eV offers a puzzling problem in high energy astrophysics. The first event of this class of phenomena was observed at the beginning of the 60's by John Lindsay at the Volcano Ranch experiment, in New Mexico [1, 2]. Since then, many events were detected, at different sites, using quite distinct techniques [3-7]. If those cosmic rays are common matter, that is, protons, nuclei or even photons, they undergo well known nuclear and electromagnetic processes, during their propagation through space. Their energies are degraded by the interaction with the Cosmic Radiation Background (CMB), way before they reached the Earth [8, 9]. After travelling distances of the order of 50 Mpc, their energies should be under 10^{20} eV, thus restricting the possible conventional astrophysical objects, which could be sources of them, and those should be easily localized through astronomical instruments. On the other hand, explaining the acceleration of charge particles, on known astrophysical objects, by mean of electromagnetical forces up to energies of 3×10^{20} eV, or even greater, the only ones capable of long range and long periods acceleration, is very difficult.

We will discuss in this paper the possible sources for the ultra high energy cosmic rays (*uhecr*), confronting what one may call conventional or bottom-up mechanisms, which attempts to explain the the ultra high energy cosmic rays through the acceleration of charged particles by electromagnetical forces in astrophysical objects, to the top-down scenario which invoke new physical process, that is, new particles and forces of nature to explain them. We discuss the techniques for the detection of the *uhecr* and their limitations and describe the status of the Pierre Auger Observatory, which is being build in Argentina, the largest project at this moment aimed at solving this puzzle. There are excellent reviews on this subject published recently and we urge the reader to go to them for more details [10-15].

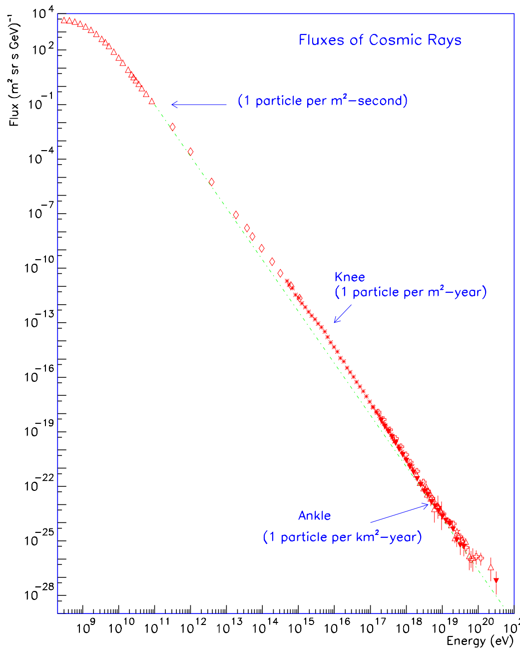

Figure 1. The cosmic ray spectrum measured at the top of the atmosphere. Above the energy of 10^9 eV the spectrum shows a power-law behavior. There is a change in slope at the *knee* (4×10^{15} eV) and at the *ankle* (5×10^{18} eV). The integrated flux above the *ankle* is about 1 cosmic ray per km^2 year (data compiled by J. Swordy).

II The high energy end of the cosmic ray spectrum

The cosmic ray spectrum, measured at the top of the atmosphere (see Fig. 1) covers a huge range in energy, going from 10 MeV to energies above 10^{20} eV, with a differential flux that spans 31 decades.

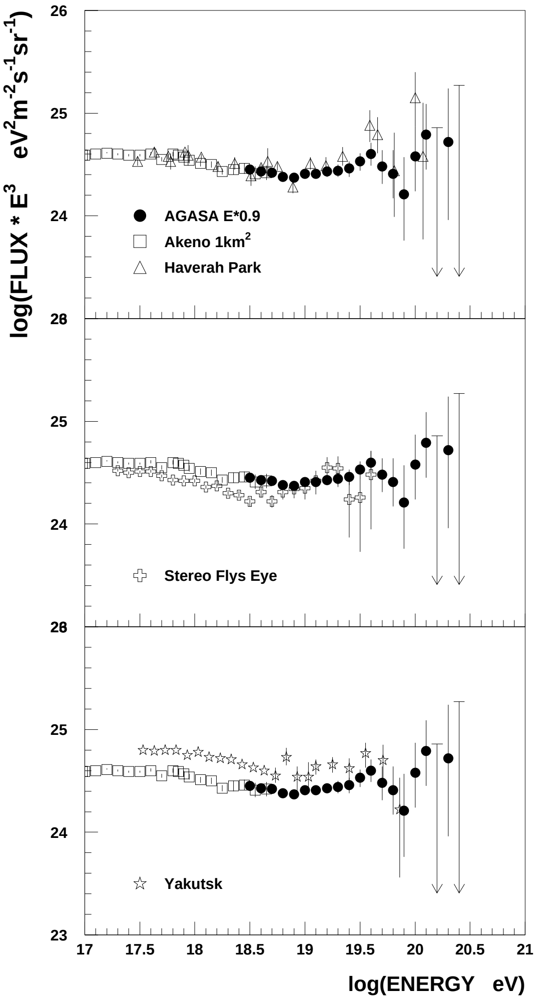

Figure 2. The high energy end of the cosmic ray spectrum measured by different techniques. There is a hint of a second *knee* at 6×10^{17} eV (from reference [12]).

The techniques to survey this spectrum goes from instruments aboard satellites flights, balloons borne detectors, to counters that monitors the fluxes of neutrons and muons at the Earth surface, and at higher energies to wide area arrays of particle detectors. The spectrum can be divided into four regions with very distinct behavior (see Fig.1). The first one, with energies below 1 GeV, have a very distinctive character from the rest of it. Its shape and cut-off is strongly dependent on the phase of the solar cycle, a phenomenon known as *solar modulation.* Actually, there is an inverse correlation between the intensity of cosmic rays at the top of the atmosphere and the level of the solar activity [16, 17].

The region above 1 GeV show a spectrum with a power law dependence, $N(E)\ \mathrm{d}E = K\ E^{-x}\ \mathrm{d}E$, where the spectral index x varies as $2.7 < x < 3.2$. The region between 1 GeV and the *knee* region at 4×10^{15} eV, is characterized by an index $x \simeq 2.7$. These cosmic rays most likely are produced at supernova explosions, its signature being in their chemical composition. When compared with the chemical composition of the solar system, that of the cosmic rays show some striking differences [18, 19], offering some clue to their origin. The elements carbon, nitrogen, oxygen and those from the iron group have the same relative abundance in the solar system and in the cosmic rays. They are the primary products of supernova explosions. There is a relative excess in the light elements lithium, beryllium and boron, as for those with atomic numbers just below iron. This excess is produced by the nuclear interaction of the primary nuclei, carbon, nitrogen, oxygen and other elements including iron, and the atoms and molecules of the interstellar gas, a process known as *spallation.* The detailed study of the chemical composition of the cosmic rays offer a window to understand the the gas distribution within the galaxy. At the knee (4×10^{15} eV) the power law index steepens to 3.2 until the so called *ankle*, at 5×10^{18} eV. The origin of the cosmic rays in this region is unclear and subject of much conjecture. Above the ankle the spectrum flattens again to an index $x \simeq 2.8$ and this is interpreted by many authors as a cross over from the steeper galactic component to a harder extra galactic source for the cosmic rays [11, 13].

We will focus, in this summary, on the cosmic rays with energies above 10^{19} eV. We show in Fig. 4, this end of the spectrum, scaled by E^3, as seen by the experiments, which use different techniques to measure them (figure from [12]). From this class of events one can pick up at least a dozen with energies which exceeds 10^{20} eV

An energy of 10^{20} eV corresponds to the classical energy of 16 J, concentrated on a single particle. To have an insight of its meaning, the 100 km or so of atmosphere is Lorentz contracted to less than a micron, from the point of view of a particle like this. At this energy, if was a neutron, it would have a decay length of about 860 kpc, allowing it to cover more than ten times the distance from the Center of the Galaxy to the Earth. Actually, if neutrons would be emitted, at these energies, in our neighboring galaxy Andromeda, a substantial amount of them would survive crossing the void to the Milky Way.

III Cosmic accelerators

There are two scenarios for the production of the ultra high energy cosmic rays. They are produced either by action of electromagnetic forces, bringing charged particles from rest to their final energies or through the decay of some very heavy exotic object still unknown to us. Protons lose their energy through pion photoproduction reactions with the cosmic microwave background (CMB), leading to an effective cutoff on the distances they can travel, at energies above 5×10^{19} eV. The role of this reaction, $\gamma + p \rightarrow \Delta(1236) \rightarrow \pi + N$, was recognized by Greisen, Zatsepin and Kuzmin (GKZ cutoff) [8, 9].

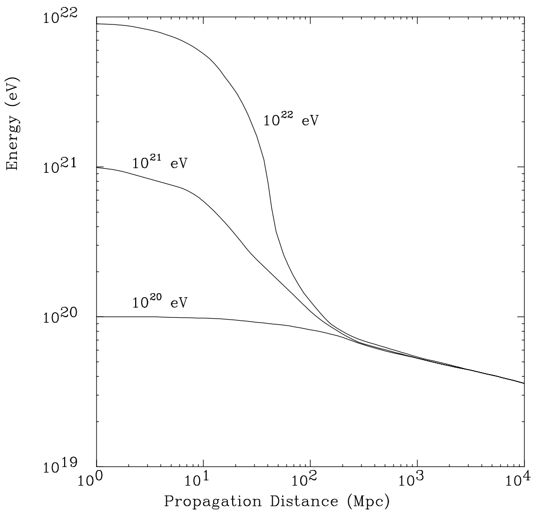

Figure 3. The energy attenuation of particle as the cross the cosmic background radiation CMB [20].

The gammas interact with background photons from the CMB, or with infrared or radio waves, leading to similar cutoffs at lower energies. Neutrinos are only known particles capable of crossing the CMB haze, up to cosmological distances, without degrading its energy. We show in Fig. 3 the degradation in energy of protons with different initial energies as they cross the 2.7 K cosmic microwave background. The high energy photons crossing the intergalactic space collide with the infrared, optical, CMB and radio waves, producing e^+ e^- pairs. This is shown in Fig. 4, where it can be seen that above 3×10^{12} eV their attenuation length is below 100 Mpc, making the Universe quite opaque to energetic photons. Electrons and positrons cannot survive to far at very high energy, they will very quickly radiate their energy away in electromagnetic cascades.

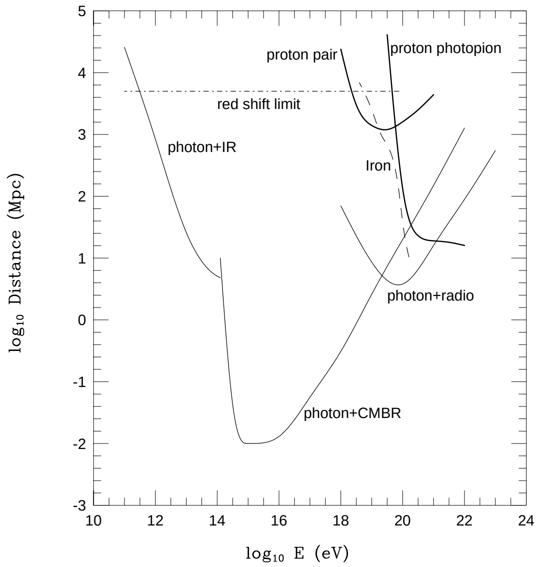

Figure 4. The attenuation length for photons. The upper line (red shift limit) is the distance limit due to the age of the Universe.

III.1 Particle acceleration

There are at least two mechanisms for the acceleration of particles up to high energies. They either undergo a one shot process, in a large distance coherent field, such as those nearby highly magnetized neutron stars or the region of the accretion disks of black holes, or they could be accelerated to very high energies, by large scale shock waves with a turbulent flow of electromagnetic fields, in a sort of *cosmic pinball machine*. These shock waves travel at speeds close to that of the light. The maximum energy, that can be archived by particles accelerated by these large scale fields, is limited by the requirement that the gyroradius of the particle must be contained in the acceleration region. Thus,

$$E_{max} = ZeBL,$$

where Ze is the charge of the particle, B the magnetic field characteristic of the region and L the length of coherence of the magnetic fields. The diagram in Fig. 7 shows the typical scales for the dimensions and the magnetic fields of the possible astrophysical sources for the ultra high energy cosmic rays [21]. From the Hillas diagram one may identify some astrophysical sources:

Neutron stars: Neutron stars are capable of accelerating ultra high energy cosmic rays [14], however this mechanism is limited by the synchrotron losses that even protons will suffer in small regions.

Active galactic nuclei (AGN): The cosmic rays can be accelerated in AGN, either at the central region or at their radio lobes. At the central regions of the AGN there are powerful engines that give rise to jets and the radio lobes. They are supermassive black holes sipping matter in accretion disks. These black holes beam jets, which create hot spots within the galaxies, as their hit large clouds of gas in the galaxy. It is estimated that the most powerful will accelerate particles above the GKZ cutoff via the first order Fermi mechanism [22, 23, 24, 25]. Here again the most severe limitation to the power of this accelerator comes from the sources of losses due to intense radiation present at the AGNs.

Cluster of galaxies: Cluster shocks could be the sites for cosmic rays acceleration, since the accelerated particles can be contained within the cluster. However, the losses due to photopion production during the propagation inside the cluster region limits the energy which can be achieved, to values at most of 10^{19} eV [26].

Gamma ray bursts: There is speculation that the sources of the high energy transient phenomena, know as gamma ray bursts, and the high energy cosmic rays may be the same [27, 28, 29]. The gamma ray bursts are distributed isotropically in the sky, however their high frequency argues against a common origin, if they are to be produced within the GKZ bounds [30].

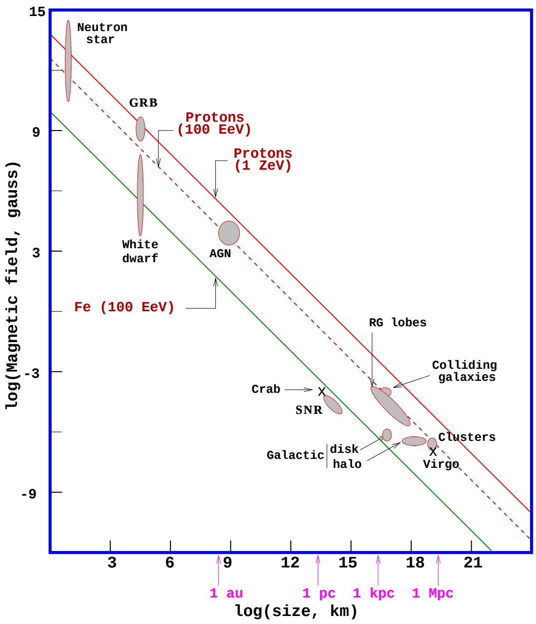

Figure 5. Size of astronomical objects versus their typical magnetic field (from A. H. Hillas [21]).

III.2 Exotic particle decay

The alternative to the acceleration scenario, or the *bottom-up* scenario, is to introduce new kind of metastable superheavy particles, say the Z particles. This particles, if they exist, must decay into common matter, made of quarks and leptons. There are a few constraints on the nature of these particles: a) their mass must be larger than the highest energy measured in cosmic rays, larger than 3×10^{20} eV. Particles associated to Grand Unified Theories (GUT), in the range of 10^{24} to 10^{25} eV, are natural candidates for those particles; b) the decay should have happened within the region of 100 Mpc radius, so that the charged particles can reach the Earth; c) their production rate density must be compatible with the observed flux of ultra high energy cosmic rays. At least two classes of production mechanism have been discussed in the literature [14]:

Ripples in space-time: The annihilation of topological defects were the first mechanisms to be proposed as possible sources of ultra high energy cosmic rays [31, 32, 33]. The defects are created at the end of the inflationary period and survive until they collapse or annihilate. The decay products are jets of hadrons, mostly pions. They have a predominance of γ-rays and neutrinos and a QCD fragmentation spectrum which is harder than in the case of shock acceleration. There are many proposals that come under the heading of topological defects, like monopoles [34, 35], cosmic strings [36, 37], vortons [38, 39], necklaces of strings and monopoles [34, 40], to name a few.

Super heavy archeological particles: The possibility that the UHECR are the products of the decays of supermassive metastable dark matter which would populate the galactic halo, was put forward some time ago [41, 42, 43]. They would lead to a nearly isotropic distribution of UHECR. Supermassive bound states from string hidden sectors, the *cryptons* are motivated by string M-theories [44]. In this class of theories there are proposals inspired by supersymmetry [45], that invoke new stable particles which do not interact with matter and have a high energy threshold in the interaction with the background radiation.

As a more radical solution to evade the GKZ limit suggests the possibility that Lorentz invariance could be broken [46]

IV Terrestrial detectors

The ultra high energy cosmic rays hit the air molecules starting an extensive air shower as the fragments of the first collision hit other nuclei, producing cascades of pions. The neutral pions start an electromagnetic shower of photons, electrons and positrons. The charged ones will strike other atoms or decay into muons and neutrinos or eventually survive until the ground. The extensive air shower can be imagined as a very thin pancake of particles, gammas, electrons, positrons, muons and some hadronic matter, crossing the atmosphere at the speed of light. The atmosphere works as a giant calorimeter, were the Molière radius is of the order of 76 m, in contrast to the few cm which it is in lead. The core of the disk has a high density of particles which then falls sharply as one get away from it. For cosmic rays at 10^{20} eV, the lateral density of particles can be, still, above one charged particle per square meter at distances of a few kilometers from the core of the shower. As a rule of thumb one may say that in the shower, for every muon, there is 10 electrons or positrons and about 100 photons.

The measurements of the ultra high energy cosmic rays have to determine their direction of arrival, which is reasonably easy to do, their energy, which is moderately easy to achieve and, their chemical composition, which is very difficult.

To measure the cosmic rays one may take a snapshot of the cross section of the shower, as it hits the ground. However, as the flux is very low, one has to expose an extensive area, which runs into the hundreds of square kilometers at present to thousands of square kilometers in the next generation of experiments (see below). A typical arrangement consists of measuring stations, with an exposure area of a few square meters, which is sensitive to the amount of particles that transverses it. The stations are spread over a large areas, with a separation between them dependent on the threshold of energy one wants to set in the array. The footprint of a typical 10^{19} eV shower is about 10 km^2, so that a separation of 1.5 km between the stations will activate about 10 stations, allowing for a good direction reconstruction. The separation between stations vary among the surface arrays, but are typically on the range between a few hundred meters and a little above 1.5 km. The angular resolution in this sort of array is better than 3°. The detector stations in this class of arrays are either scintillation counters or Čerenkov detectors. Some arrangements use buried scintillation counters to identify the muonic component of a shower. The energy of the shower is identified by the density of charged particles in a ring, at a large distance from the core, typically about 600 m [47]. The correlation between this density and the primary energy is inferred from shower simulation and is quite independent of the primary composition. The identification of the primary chemical composition using surface arrays is difficult, for it relies on subtle differences on the muonic radial distribution in relation to the electromagnetic component of the shower [48, 49].

The other technique which has been used to measure the ultra high energy cosmic rays, make use of the light emitted by the fluorescence of the excited nitrogen atoms and molecules along the path of the shower. This light, emitted mostly in the UV region, with wavelength between 300 and 400 nm, can be collected by telescopes standing far away. The yield of photons varies very little with the altitude, about 4.6 photons per meter of electron track of the shower. The intensity of their emission is proportional to the total number of electrons tracks at each stage of the shower, giving a longitudinal profile measurement of the shower development. This allows for a direct and more precise measurement of the energy of the shower, without dependence on theoretical models for showers. The direction of the shower is extracted from a geometrical reconstruction of the evolution of the signal.

The depth of the shower maximum (defined in g/cm^2), for a given energy is dependent on the primary composition, so in experiments, if the resolution is sufficiently fine, the measurement of X_{max}, the position of maximum development of the shower, will be a discriminator of the nature of the primary cosmic ray. However, fluorescence detectors can only operated in the evenings, when the sky is clear and moonless, which amounts to a 10% duty cycle during the year.

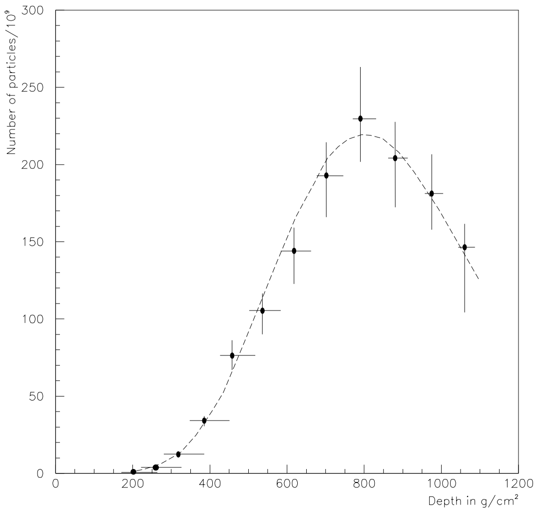

Figure 6. Longitudinal profile of the Fly's Eye event with energy 3×10^{20} eV (from refe. [50]).

V The Pierre Auger Observatory

The Pierre Auger Observatory, which is composed of two sites, one in the Southern Hemisphere and the other in the Northern, is optimized to measure the characteristics of cosmic rays with energies above 10^{19} eV. It uses a hybrid technique, that is, it has a ground array, the Surface Detector (SD), made of 1600 Čerenkov detectors and four fluorescence light detectors (FD) at each hemisphere site[51].

The Southern site, nearby the city of Malargüe, in the Province of Mendoza, covers an area of 3 000 km^2 with stations set in a triangular grid, with 1.5 km separation between them. Each tank is a Čerenkov light detector, a cylinder with an exposure area of 10 m^2 and about 1.5 m high, filled with 12 000 l of purified water. The tanks have an internal liner, made of Tyvek sandwiched with plastic, designed to diffuse the ultraviolet Čerenkov light. The light is collected by three photomultiplier tubes, with 20.3 cm diameter, set in a symmetric pattern on top of the tanks. The electronics for the detectors are housed in a box outside the tanks and communicate with the central station through a radio WLAN, operating at 915 MHz band. The stations are powered by solar panels and batteries. The time synchronization of the tanks is based on a GPS system, capable of a time alignment precision of about 10 ns.

The Fluorescence Detector (FD) is composed of 5 eyes in 4 locations. Each eye covers an angle of 180°

in azimuth and 30° elevation from the horizon. Three of the eyes are in the periphery of the site, looking inwards, while the other two are at the same location, near the center of the surface array, actually covering an angle of 360°. Each eye has six independent telescopes, with a field of view of 30° × 30°. The fluorescence light is collected by a mirror with a radius of 3.1 m and reflected into a camera, located at the focal surface of the mirror. The image of a point of light in the sky is kept focused into a spot, at the focal surface, of 0.25° radius, by a diaphragm, with a diameter of 1.87 m, at the center of curvature of the mirror. The camera, which has an area of one square meter, is composed of 440 pixels, each a hexagonal photomultiplier, which monitors a solid angle of $(1.5°)^2$ projected into the sky. The dead spaces between the photomultipliers is corrected by a device, called the *Mercedes corrector* [52]. The operation of the FD is limited to clear nights, with very little moonlight, which in effect, mean a duty cycle a little bit over 10% of the overall running time of the experiment. The SD operates at all times during the year.

The hybrid mode operation offers a way to cross-calibrate the detectors and improves the energy and angular resolution of the observatory. For showers with energies above 10^{19} eV (10 EeV), the triggering efficiency is above 90%, while it reaches virtually 100% at 100 EeV. The energy resolution for showers of 10 EeV is estimated to be around 30% for the SD operating alone, improving to better than 20% for the hybrid mode of operation. At 100 EeV the resolution is improved quite a lot, to 15% and 10% respectively. As for the angular resolution at 100 EeV, it is estimated to be 1° for operation with the surface detector alone, but goes down to 0.20° for the hybrid mode. The statistics for the 100 EeV cosmic rays is expected to increase ten-fold in relation to the number of showers measured up to date, in just one year of full operation of the Observatory.

During the year 2001, the first stage of the construction of the Pierre Auger Observatory will be completed. That is the so called *Engineering Array* (EA) phase. The team working at the site have already laid 40 Čerenkov tanks, set in a hexagonal array, covering an area of 54 km^2, with two of the tanks, at the center of the array, laying side by side, in order to cross calibrated their signals. This ground array is overlooked by two telescopes sitting on top of the hill of Los Leones, 60 m above the plan of the array. At the moment of writing, the electronics of the tanks are being mounted and before the middle of 2001, the whole EA will be operational. One of the challenges of this first stage of the observatory will be to check the observation by the AGASA experiment of a 4.5 σ event excess, coming from the direction of the center of our Galaxy, in the region between 8×10^{17} eV and 2×10^{18} eV [53](see Fig. 7).

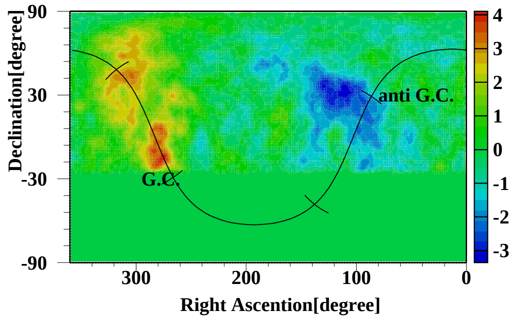

Figure 7. Asymmetry at CG at 18.7 eV seen by Akeno. (from reference [53]).

One of the interesting capabilities of the Auger observatory is its sensitivity to ultra high energy neutrinos [54]. The Earth is opaque to UHE neutrinos [55], however, they will interact deeply in the atmosphere, in contrast to hadrons or electromagnetic particles. The neutrinos have a small cross section with the matter in the atmosphere, so it has a homogeneous probability to interact at any point of it. The electromagnetic component of the normal showers, with are generated in the atmosphere, are suppressed sharply at slant depths which correspond to zenithal angles of about 60° [56]. The estimate of the acceptance of a single eye Fluorescence Detector for the Auger Observatory is shown in Fig. 8.

VI Summary and conclusions

We have given a brief review of the current status of research in the field of ultra high energy cosmic rays. The existence of cosmic rays with energy that exceeds 10^{20} eV is confirmed by experiments using different techniques. These cosmic rays challenge conventional explanations for their production and propagation through space. Acceleration mechanisms, which invoke electromagnetic fields for this, associated to astrophysical objects, do not offer a compelling explanation for the production of these extreme energies particles. On the other hand, the *top-down* mechanisms appeal to new particles, not yet observed, implying new kinds of physical laws. There is an observatory, now in construction, the Pierre Auger Observatory, which will address these problems, pushing the sensitivity of detectors to higher energies and adding at least two order of magnitude to statistics of existing events. The first site of this observatory, being built in the Southern Hemisphere, will be particularly sensitive to any peculiar activity associated to the center of the Milky Way galaxy. The construction of the southern observatory is on schedule and should see the first shower by the middle of this year.

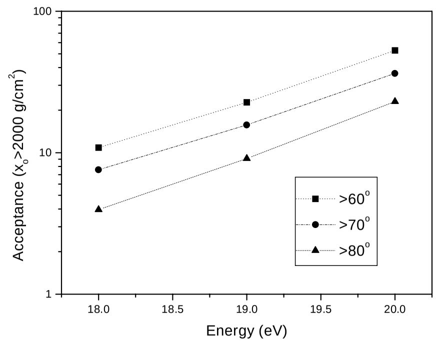

Figure 8. The neutrino acceptance of the fluorescence detector of the Pierre Auger Observatory. (from reference [54]).

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