GAP-96-045

Project update presented at the International Symposium on Extremely High Energy Cosmic Rays: Astrophysics and Future Observatories, Tanashi, Tokyo, Japan, 25-28 September, 1996

The Pierre Auger Project

Paul M. Mantsch

Fermi National Accelerator Laboratory

Abstract. The Pierre Auger project is a broadly based international effort to make a detailed study of cosmic rays at the highest energies. Two air shower detectors are proposed, one to be placed in the Northern Hemisphere and one in the Southern Hemisphere. Each installation will consist of an array of about 1600 particle detectors spread over 3000 km^2. Each installation will also have three atmospheric fluorescence detectors viewing the volume above the surface array. These two air shower detector techniques working together form a powerful instrument for the proposed research. The objectives of the Pierre Auger project are to measure the arrival direction, energy, and mass composition of 60-90 events per year above an energy of 10^{20} eV and 6000-9000 events per year above 10^{19} eV. A collaboration has been formed with the goal of having the Pierre Auger observatory in operation by 2002.

Introduction

The Pierre Auger Project is an effort by a broad international collaboration to conduct an all sky survey of the highest energy cosmic rays. Two cosmic ray observatories, each with an aperture of 6000-9000 km^2-sr are proposed, one in the Northern hemisphere, and the other in the Southern hemisphere. Air shower detectors at these observatories will measure the energy spectrum, direction, and nuclear composition of cosmic rays with energies above $5 * 10^{19}$ electron Volts.

In the past thirty years, nine cosmic ray air shower events have been observed in which the cosmic ray primary had an energy at or in excess of 10^{20} eV. Recently, two events well in excess of 10^{20} eV have been reported. In 1991, the Fly's Eye group using an air fluorescence detector observed an air shower with a measured primary energy of $3.2\ (+0.4-0.5)*10^{20}$ eV.[1] In 1993, the group working at the AGASA array in Akeno, Japan, reported an event with energy of $(1.7-2.6) * 10^{20}$ eV.[2]

These very high energy particles raise baffling mysteries. Known acceleration processes in astrophysical objects cannot be identified for particle energies in excess of 10^{20} eV. Another mystery is that space becomes opaque to particles with energies in excess of $5*10^{19}$ eV because of the 2.7 K cosmic microwave background. This limitation implies that the sources for these ultra high energy particles need to be less than about 50 Mpc from the earth. Particles with energies in this range are expected to be deflected very little by magnetic fields within or

[1] D. J. Bird, et. al., Phys. Rev. Letters 71, 3401 (1993).
[2] N. Hayashida, et. al., Phys. Rev. Letters 73, 3491 (1994).

beyond the galaxy. Yet none of these high energy cosmic rays points back to a possible source.

The cosmic ray flux falls very rapidly with energy so that at an energy of 10^{19} eV, the flux is $1/km^2/sr/year$. At 10^{20} eV, the flux is about $1/km^2/sr/century$. The proposed Pierre Auger observatory will be sufficiently large to study the details of the high end of the cosmic ray spectrum which, together with the direction and nuclear composition, will provide clues to the origin of the highest energy cosmic rays.

Propagation of High Energy Particles in Space

Understanding the origin of energetic charged particles depends on a knowledge of magnetic fields through which they travel. If the fields were uniform and the order of 2-3 μGauss near the galaxy, light nuclei (like oxygen) are just barely contained by the galaxy while protons of this energy must have extra galactic origins. Given our understanding of fields within the galaxy and intergalactic space cosmic ray protons near 10^{20} eV will suffer only a few degrees deflection from nearby sources.

The cosmic microwave background degrades the energy of cosmic rays coming from extended distances. Not long after Penzias and Wilson discovered microwave background radiation,[3] Greisen[4] and Zatsepin and Kuzmin[5] independently pointed out that this radiation would make space opaque to cosmic rays of very high energy. A 2.7 K photon will, in the rest frame of a sufficiently energetic proton, interact to produce pions. High energy nuclei will be subject to photo disintegration. The "Greisen-Zatsepin/Kuzmin Cutoff" takes effect at energies greater than about $4*10^{19}$ eV. The result is that high energy cosmic rays above the cutoff are expected to come from distances less than about 50 Mpc.

Possible Sources

Shock acceleration in galactic supernovae can account for energies to about 10^{15} eV. Violent activity in astrophysical objects such as powerful radio sources, and active galactic nuclei can account for much higher energies. No mechanism, however, has been identified that will give rise to the highest cosmic rays observed. Among possible candidates, there are none within 100 Mpc of the earth.

There are more exotic possibilities for sources. A curious coincidence between the energy flow of the highest energy cosmic rays and gamma ray bursts suggests a possible common source.[6] Another speculation is that very high energy cosmic rays may be the result of annihilation of topological defects left over from the early

---

[3] A. A. Penzias and R. W. Wilson, Ap. J. 142, 419 (1965).
[4] K. Greisen, Phys. Rev. Letters 16, 748 (1966).
[5] G. T. Zatsepin and V. A. Kuzmin, JETP Letters 4, 78 (1966).
[6] E. Waxman, Phys. Rev. Lett. 75 386 (1995).

universe. The energy scales of such events are of the order of 10^{24} eV.[7] Beyond these ideas is the possibility that the highest energy cosmic rays are evidence for new particle physics or new astrophysics.

At the beginning of this symposium Professor Jim Cronin has described the current understanding of sources in detail.

A recent very tantalizing report from the AGASA Group[8] shows three instances in which pairs of particles come from the same location on the sky near the super galactic plane. The chance probability of seeing these three pairs within the direction resolution is about one percent. The confirmation of point sources of high energy cosmic rays would be enormously exciting.

Extensive Air Showers

The highest energy cosmic rays can only be observed on the earth by way of their interaction in the earth's atmosphere. Cascades of particles, first observed by Pierre Auger in 1938,[9] are initiated by cosmic ray particles striking air molecules. The shower cascade peaks at a depth of about 700 gm/cm^2 in the atmosphere. The shower arrives at the earth's surface as millions of particles. Gammas (~89%) and electrons (~10%) of about 10 MeV dominate. There are also muons (~1%) with energies of about 1 GeV.

The shower particles arrive spread in time depending on the distance from the shower core. For a 10^{19} eV shower observed about 1 km from the core, muons come first between 0.1 and 1 μs. Gammas and electrons come up to about 5 μs later. Heavier nuclei tend to shower earlier in the atmosphere. This results from the distribution of energy among the nuclear collision fragments. The collision fragments will have less energy and will spend their energy higher in the atmosphere. As the energy of charged pions decreases, they are also more likely to decay to muons before interacting. The depth of shower maximum and the ratio of electromagnetic particles to muons, therefore, provide an indication of the primary mass.

Air Shower Detector Methods

The two most commonly used methods for air shower measurements are those detecting atmospheric fluorescence and those measuring particle densities on the surface. On dark moonless nights, nitrogen fluorescence produced by air shower induced ionization can be detected by a sky covering array of photomultipliers. This method was pioneered by the Fly's Eye group at the University of Utah. The fly's eye type detector observes the shower as a spot of light moving across the

---

[7] P. Bhattachorjee, C. T. Hill, D. N. Schramm, Phys. Rev. Lett. 69, 567 (1992).
[8] N. Hayashida et al., PRL 77, 1000 (1996)
[9] P. Auger et. al.., Comtes Rendas 206, 1721 (1938).

sky. By measuring the amount of light and timing of the photons, the fly's eye can directly measure the energy deposition profile.

Particle detector arrays are the more traditional method of air shower detection. Particle detectors are spaced out on the ground. The particles in the shower are shaped like a thin pancake moving near the speed of light. The timing of the particles as they strike elements of the array can be used to determine the direction of the shower (and primary) direction to about 2 degrees. The measured particle density profile at the ground can be used to infer the primary particle energy. The number of muons and the rise time of the pulse in the particle detectors is used to infer the primary particle mass.

Of the two air shower detection methods, fluorescence detection provides a more direct measure of the energy. The light due to ionization is a measure of the electromagnetic shower size and hence the energy. Surface detectors, on the other hand, depend on comparison to simulated showers. Although the earliest interactions of the simulated showers depend on particle production models that extrapolate from accelerator data, the particle densities on the ground are rather insensitive to these processes. Energy determination depends, therefore, on well understood cascade processes. As a result, high energy cosmic ray spectra measured by fluorescence detectors and ground arrays agree within 20 to 30%. Since fluorescence detectors only work on dark cloudless nights, they have a 10% duty cycle as compared to the surface array.

The Pierre Auger Project

The Pierre Auger Project had its conception in a series of workshops in Paris (1992), Adelaide (1993), Tokyo (1993), and finally at Fermilab in 1995. The leaders in these workshops were Professors Jim Cronin of the University of Chicago and Alan Watson of the University of Leeds. The Design Group for the Auger Project, hosted by Fermilab, met from January 30 through July 31, 1995. More than 140 scientists from 17 countries attended one or more of the conferences and topical workshops. A design report containing a reference design and a cost estimate for the proposed detector was issued in October 1995. In November of 1995 a meeting was held in Paris to form the collaboration and to choose the site in the Southern hemisphere. In September of 1996 a collaboration meeting held in San Rafael, Argentina to choose the Northern site and to hold a design requirements review.

The objectives of the Auger Project are to study the cosmic ray energy spectrum in the range 10^{19} to 10^{21} eV and to look for sources of the highest energy cosmic rays. The detectors in the two sites together are designed to collect 6000-9000 events per year above 10^{19} eV and 60-90 events per year above 10^{20} eV.

The Pierre Auger Observatory will build a powerful air shower detector by combining the strengths of the fluorescence and ground array detectors. In the surface array mode with 100% duty cycle the detector will gather high statistics. It will have full sky coverage using simple detectors over a well known collecting area.

The following measurement precision for the ground array is expected:

	10^{19} eV	10^{20} eV
Space angle	< 2.5°	< 1.5°
Energy	25%	20%

Primary Mass heavy (Fe) . medium (O) . light (p)

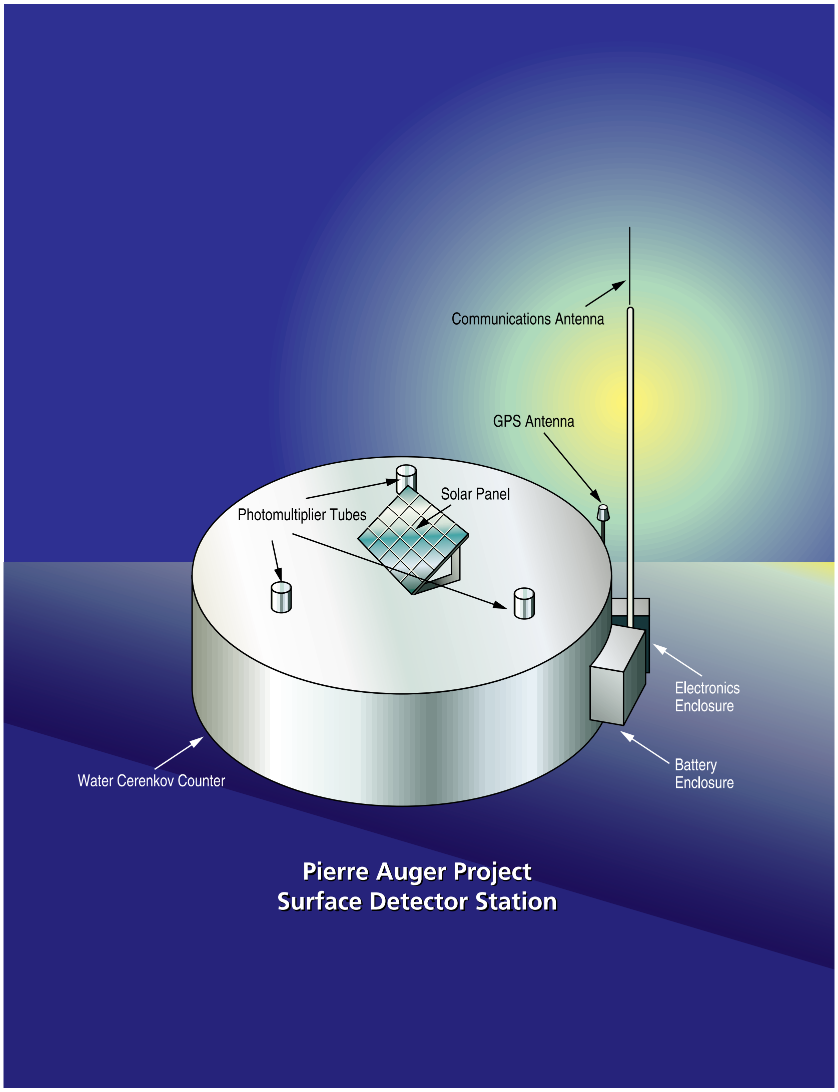
During the hybrid mode with 10% duty cycle the fluorescence detector will make a calorimetric energy measurement and will record a direct view of the shower development (Xmax). The ability of the fluorescence detector to detect the shower profile will be good for the detection of γ ray induced showers where the LPM effect will deepen shower development. During operation of the hybrid array the space angle precision will be less than 0.5˚.

The hybrid detector proposed for the Auger Project has important advantages over either surface detectors or fluorescence detectors used alone. In the hybrid mode each detector can make an independent measurement of primary particle energy, direction and composition. The hybrid mode will provide an excellent way to control the systematic errors inherent in each method alone. Furthermore fluorescence and surface detectors used together can produce a more reliable measurement of the energy and angle. That is possible because the shower front timing and core position from the surface array together with the fluorescence data leads to a much more precise measurement of angle than from a single fluorescence detector. The particle density at the surface also provides an energy correction for the part of the shower not visible to the fluorescence detector. The two techniques also measure the primary mass in complimentary ways. The fluorescence detectors make an estimate of the mass by measuring the depth of shower maximum while the surface detector measures the muon rise time and muon to electromagnetic ratio which is also related to primary mass. The measurement of energy by the hybrid detector combination will calibrate the energy measurement when the surface array is in operation alone, about 90% of the time.

It should be noted that the Auger detector will also be sensitive to neutrino showers initiated at very large zenith angles. The effective target volume exceeds 10^4 Km^3 of air for events above 10^{19}eV.

In the current baseline design each site will have three full sky fluorescence detector stations. Each fluorescence detector station will consist of 48 mirror units that cover the whole sky. One hundred photomultipliers will view each mirror. Four mirror units are located in each enclosure.

The design for the surface detector is the water Cerenkov detector. An artists' conception is shown in the figure. The detector consists of a water tank 10 square meters in area, 1.2 meters high, containing 3000 gal (11,000 l) of filtered deionized water. The water is viewed from above by three 8 in. (200 mm) photomultiplier tubes. The choice of water over detector designs using plastic scintillator, for example, was based on cost and reliability. The experience of Haverah Park air shower array in the UK using water Cerenkov detectors showed that such counters can operate reliably for 20 years.



Conceptual design for the Water Cerenkov detector for use in the surface array.

Each detector station is powered by a 10 watt solar power system. A radio transceiver provides communication with neighboring tanks and a central data station. There is a Global Positioning Satellite (GPS) receiver on each station for timing (50 ns absolute, 10 ns relative).

The surface array is expected to have three levels of triggering. Level 1 requires several particles in a station spaced in time, reducing the countering rate to about

100 Hz from a 5 kHz singles rate. Level 2 analyzes the flash ADC wave form from the station to reduce the trigger rate from 100 Hz to about 20 Hz. All data from level 2 will be recorded. Level 3 will require level 2 triggers in neighboring tanks indicating the presence of a shower. The shower trigger rate should be about 0.2 Hz.

Detector R&D

Prototype surface array water Cerenkov detectors are now in operation in three locations to study various aspects of performance and construction. Perhaps the most important studies are those underway with water detectors in the AGASA array in Akeno, Japan. Several events above 10^{18} eV in coincidence with AGASA have been recorded. A second tank will soon be deployed near the center of the array at Akeno.

Another tank is being used at Tandar Laboratory in Argentina to study optimum phototube position and tank construction methods. Development work on water additives to control biological growth is also based in Argentina. A third tank is in place at Fermilab to study the performance of lining materials and water transparency. It is hoped to also have a tank in operation soon at Puebla, Mexico.

Studies to verify the hybrid techniques are underway in Dugway, Utah where the HiRes fly's eye prototype over looks the CASA/MIA array. A number of showers seen by both detectors have been recorded. The results are very encouraging. (See talk by C. Jui in these proceedings.)

Development work in electronics communications and GPS timing is underway at other collaborating institutions. Simulations for showers and detectors response are also being carried out.

The design of the fluorescence detector is drawn largely from the HiRes detector now being built at Dugway Utah. (The HiRes detector is described by Pierre Sokolsky earlier in this symposium.)

Sites

Twenty sites in both hemispheres were evaluated in 1995 and 1996.

The basic criteria for sites were:

Latitude	30-45°
Area	~4000 km^2
Altitude	s.l. - 1500 m
Cloud cover	< 15%
Light pollution	none
Terrain	flat
Soil and vegetation	accommodate transport

Access roads, electrical power, security

The Southern site was chosen to be in Argentina in Mendoza near San Rafael. It is a very flat site near the base of the Andes mountains. The infrastructure is good and there are good roads near and on the site.

The selected Northern site is in Millard County, Utah about 150 Km southwest of Salt Lake City. Although mostly flat there are some features that stand several hundred meters above the plain that may be suitable for the installation of fluorescence detectors.

Cost and Schedule

The Auger collaboration hopes to proceed on an aggressive schedule. Detector R&D will proceed during 1997 and 1998 while funds for the project are being raised. Construction will begin in 1998 and will be completed in 2002. As soon as a reasonable complement of detectors is installed, probably a year into installation, commissioning can begin. Full operation would begin in about 2002.

The full cost of the detector was set to be less than $100 M (U.S.) The size of the surface array would be expanded or contracted to fall within that limit. Of this $100 M, approximately $27 M is allocated to the fluorescence detector, $56 M to the surface detectors, $14 M to the central station and infrastructure, and $3 M to management related expenses.

Summary

The Pierre Auger Project is a worldwide effort to uncover the mysteries of the highest energy cosmic rays. The Project will consist of two powerful air shower observatories, one in the Southern hemisphere and one in the Northern hemisphere. Two excellent sites have been chosen. An enthusiastic collaboration has been formed and submission of funding proposals is underway.