Fermi National Accelerator Laboratory

FERMILAB-Conf-96/007

The Pierre Auger Project

Paul M. Mantsch

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

January 1996

Submitted to the *Latin-American Workshop on Particles and Phenomena of Fundamental Interactions*, H. Puebla de Z., Mexico, October 29-November 3, 1995

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

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 1600 particle detectors spread over 3000 km^2 with a solid angle acceptance of 2 sr for cosmic ray air showers. Each installation will also have an atmospheric fluorescence detector 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 events per year above an energy of 10^{20} eV and 6000 events per year above 10^{19} eV. A collaboration is now being formed with the goal of having the Pierre Auger observatory in operation by 2001.

INTRODUCTION

It is most appropriate to talk about the Pierre Auger Project in Mexico, the home of one of the great pioneers of cosmic ray physics, Manuel Vallarta. I hope that Mexico and, indeed, all of Latin America will play an important role in the Auger Project.

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 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, eight cosmic ray air shower events have been observed in which the cosmic ray primary had an energy 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] The particles causing these events have macroscopic energies. An energy of 3.2*10^{20} (or 50 joules) corresponds to the kinetic energy of a lead brick dropped a half meter! It is an energy 10^{8} times higher than protons accelerated by the Fermilab Tevatron, the world's most powerful particle accelerator.

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

Figure 1 shows the high end of the cosmic ray spectrum as measured by the AGASA collaboration air shower array in Akeno, Japan.[3] Important features of the spectrum include a break at the "knee" (about 5*10^{15} eV) that is conjectured to be the transition from galactic to extragalactic particles. It should be noted that this energy corresponds to the maximum energy of particles accelerated by supernova remnants. There is another apparent break at the "ankle" where the spectrum flattens again. The important thing to note is that at an energy of 10^{19} eV, the flux is 1/km^2/sr/year. At 10^{20} eV, the flux is 1/km^2/sr/century! The 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 particles.

FIGURE 1. The energy spectrum of primary cosmic rays obtained at Akeno.

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. Figure 2 shows a schematic view of the deflection of charged particles with an energy of 10^{20} eV and various charges. The Larmor radius is

$$R(\mathrm{kpc}) \equiv (E_{18}/ZB(\mu\mathrm{G})$$

where E_{18} is the energy in units of 10^{18} eV. If the fields are uniform and the order of 2-3 μGauss near the galaxy, it is clear that light nuclei (like oxygen) are just barely contained by the galaxy while protons of this energy must have extragalactic origins.

FIGURE 2. Possible trajectories for 10^{20} eV particles within the Helo of the galaxy.

The cosmic microwave background degrades the energy of cosmic rays coming from extended distances. Not long after Penzias and Wilson discovered microwave background radiation,[4] Greisen[5] and Zatsepin and Kuzmin[6] 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 $5*10^{19}$eV. The result is that high energy cosmic rays above the cutoff are expected to come from distances less than about 50 Mpc. Figure 3 shows the energy degradation of cosmic rays over cosmic distances.[7]

FIGURE 3. Calculated mean energy of protons due to the interaction with 2.7°K radiation as a function of distance for various initial energies.

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.[8] Another speculation is that very high energy cosmic rays may be the result of annihilation of topological defects left over from the early universe. The energy scales of such events are of the order of 10^{24} eV.[9] Beyond these ideas is the possibility that the highest energy cosmic rays are evidence for new particle physics or new astrophysics.

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,[10] 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. A schematic of shower development is shown in Figure 4.

FIGURE 4. Longitudinal shower development.

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 sky. By measuring the amount of light and timing of the photons, the fly's eye can directly measure the energy deposition profile. Figure 5 shows the pattern on the sky observed by 800 phototubes in the fly's eye detector triggered by the $3.2 * 10^{20}$ eV event.[11] Figure 6 shows the longitudinal shower profile for this same event.

FIGURE 5. Pointing directions of Fly's Eye phototubes triggered by the $3.2 * 10^{20}$ eV shower.

FIGURE 6. Shower profile for the $3.2*10^{20}$ eV Fly's Eye event.

Particle detector arrays are the more traditional method of air shower detection. Particle detectors are spaced out on the ground shown schematically in Figure 7. The particles in the shower are shaped like a thin pancake. 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.

FIGURE 7. Illustration of cosmic ray direction measurement using air shower front.

Figure 8 shows a particle density map of the $2*10^{20}$ eV event seen by the AGASA group at Akeno, Japan.[12] This air shower struck a particularly dense part of the detector array so that the direction of the shower core was determined with good precision. The numbers indicate the particle density while the circle diameter is proportional to the log of the particle density.

FIGURE 8. Map of the density distribution of the giant air shower observed by the AGASA group. Each dot corresponds to a particle detector. The size of the circle is proportional to the logarithm of the particle density at each detector.

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, depend on well understood cascade processes. As a result, spectra from 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 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. The objective of the Design Group was to produce a design report containing a reference design and a cost estimate for the proposed detector.

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 events per year above 10^{19} eV and 60 events per year above 10^{20} eV.

The following measurement precision is expected:

	1019 eV	1020 eV
Space angle	< 2.5°	< 1.5°
Energy	25%	20%

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

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 good energy resolution, using coincident events with the fluorescence detector for calibration. It will have good direction resolution and primary mass information from muon density. In the hybrid mode (10% duty cycle) the two detectors will work together to produce excellent energy and angle resolution. For these events, the longitudinal shower development will be measured directly.

Figure 9 shows a cartoon of the Auger detector. The ideal hexagonal array consists of 1657 detector stations spaced out by 1.5 km covering a total area of 300 km^2. A fluorescence "eye" detector will be located at the center of the array. The spots shown on the sketch illustrate the size of typical showers of 10^{19} and 10^{20} eV energy.

FIGURE 9. Cartoon of the ground array with fluorescence "eye" in the center. The circles are the approximate size of 10^{19} and 10^{20} eV showers.

The fluorescence array will consist of 48 mirror units that cover the whole sky. Each mirror will be 4.4 meters in diameter and consist of 19 segments. An array of 225 photomultipliers will view each mirror.

The reference design for the surface detector is the water Cerenkov detector shown in Figure 10. The detector consists of a water tank 10 square meters in area, 1.2 meters high, containing 3000 gal (11,000 l) of filtered 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.

FIGURE 10. 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.

R&D PROGRAM

The thrust of the Auger R&D program is to develop and install prototype detector stations in the Fly's Eye/Casa detector in Dugway, Utah, and in the AGASA array in Akeno, Japan. Development for the fluorescence detectors includes effort on cameras, PMT's, mirrors, mounts, enclosures, and performance simulations. The surface detector requires development of communications, data acquisition, detector tanks, electronics, solar power, and also performance simulations.

SITES, SCHEDULE, & COST

Countries in the Southern hemisphere where sites were studied were South Africa, Argentina, and Australia. In the Northern hemisphere sites in Spain, Western US, Russia, and India were surveyed.

The criteria for sites are:

Latitude	30-45°
Area	~4000 km2
Altitude	s.l. - 1500 m
Cloud cover	< 15%
Light pollution	none
Terrain	flat
Soil and vegetation	accommodate transport
Access road, electrical power, security	

(Note added in proof: In the first Auger Project Collaboration meeting held in Paris in November, 1995, the preferred southern site was selected to be near Las Leñas in Argentina.)

The Auger collaboration hopes to proceed on an aggressive schedule. The two sites are to be chosen by mid 1996. Detector R&D will proceed during 1996 and 1997 while funds for the project are being raised. The installation will take place between 1998 and 2001. 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 $17 M is allocated to the fluorescence detector, $54 M to the surface detectors, $26 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 is conceived as two powerful air shower observatories, one in the Southern hemisphere and one in the Northern hemisphere. An enthusiastic collaboration is being formed to make the Auger Project a reality. New collaborators are welcome.

[1] D. J. Bird, et. al., Phys. Rev. Letters 71, 3401 (1993).
[2] N. Hayashida, et. al., Phys. Rev. Letters 73, 3491 (1994).
[3] S. Yoshida, et. al., Astroparticle Physics 3, 105 (1995).
[4] A. A. Penzias and R. W. Wilson, Ap. J. 142, 419 (1965).
[5] K. Greisen, Phys. Rev. Letters 16, 748 (1966).
[6] G. T. Zatsepin and V. A. Kuzmin, JETP Letters 4, 78 (1966).
[7] J. H. Cronin, et. al., Nucl. Phys. B (Proc. Suppl.) 28B, 213 (1992).
[8] E. Waxman, Phys. Rev. Lett. 75 386 (1995).
[9] P. Bhattachorjee, C. T. Hill, D. N. Schramm, Phys. Rev. Lett. 69, 567 (1992).
[10] P. Auger et. al.., Comtes Rendas 206, 1721 (1938).
[11] D. J. Bird et. al., ibid.
[12] N Hayashida et. al., ibid.

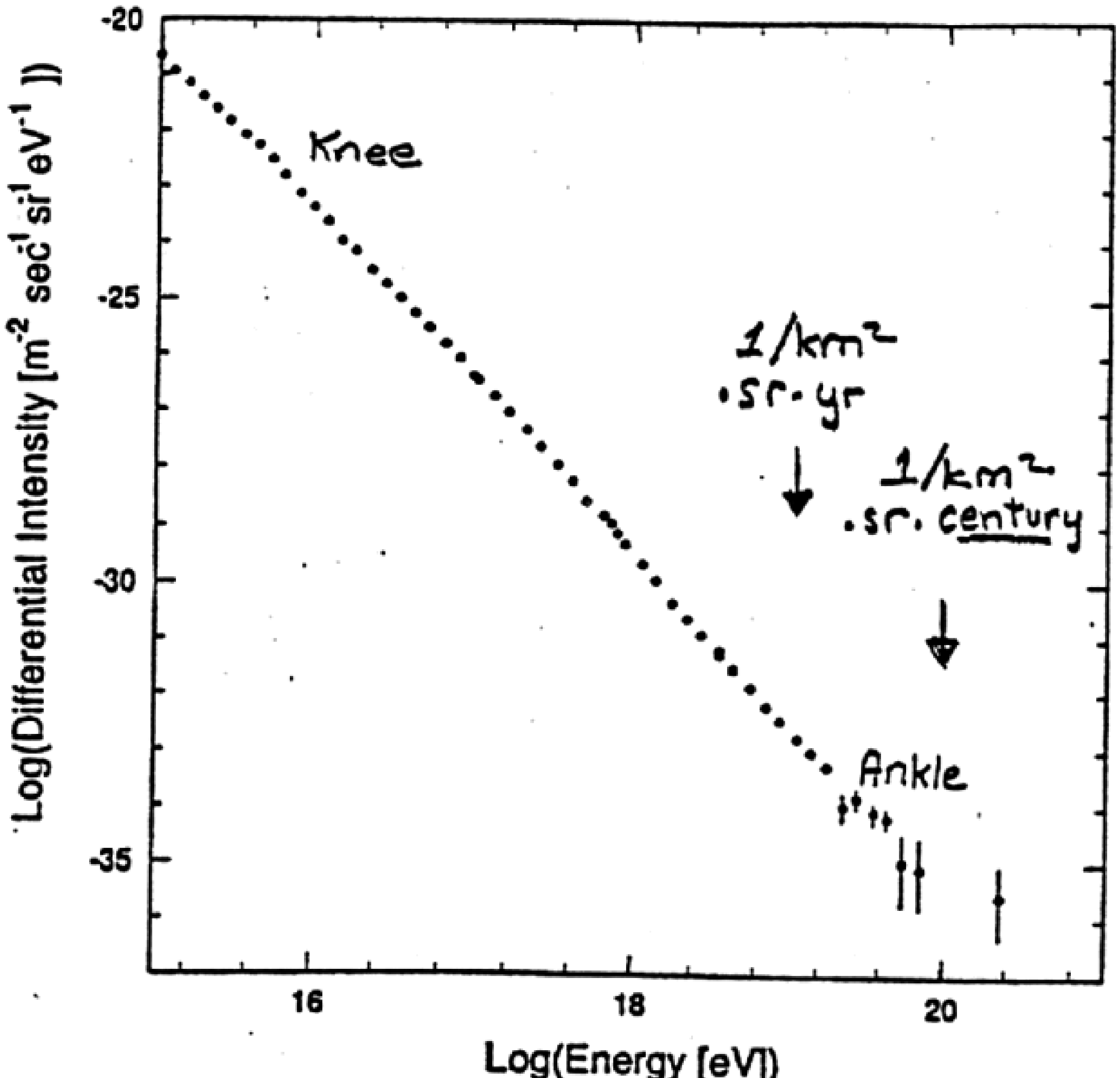

FIGURE 1. The energy spectrum of primary cosmic rays obtained at Akeno.

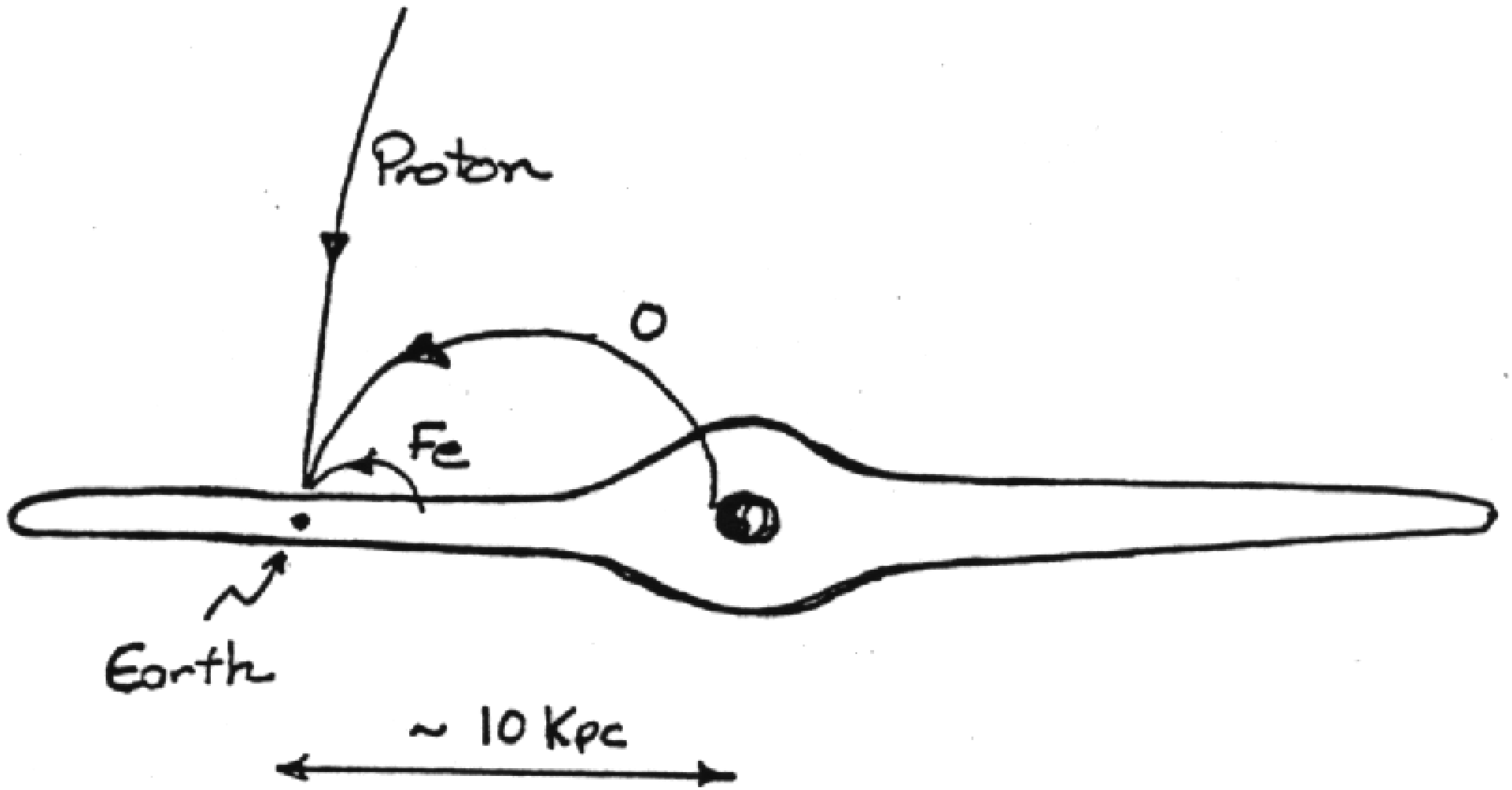

FIGURE 2. Possible trajectories for 10^{20} eV particles within the Helo of the galaxy.

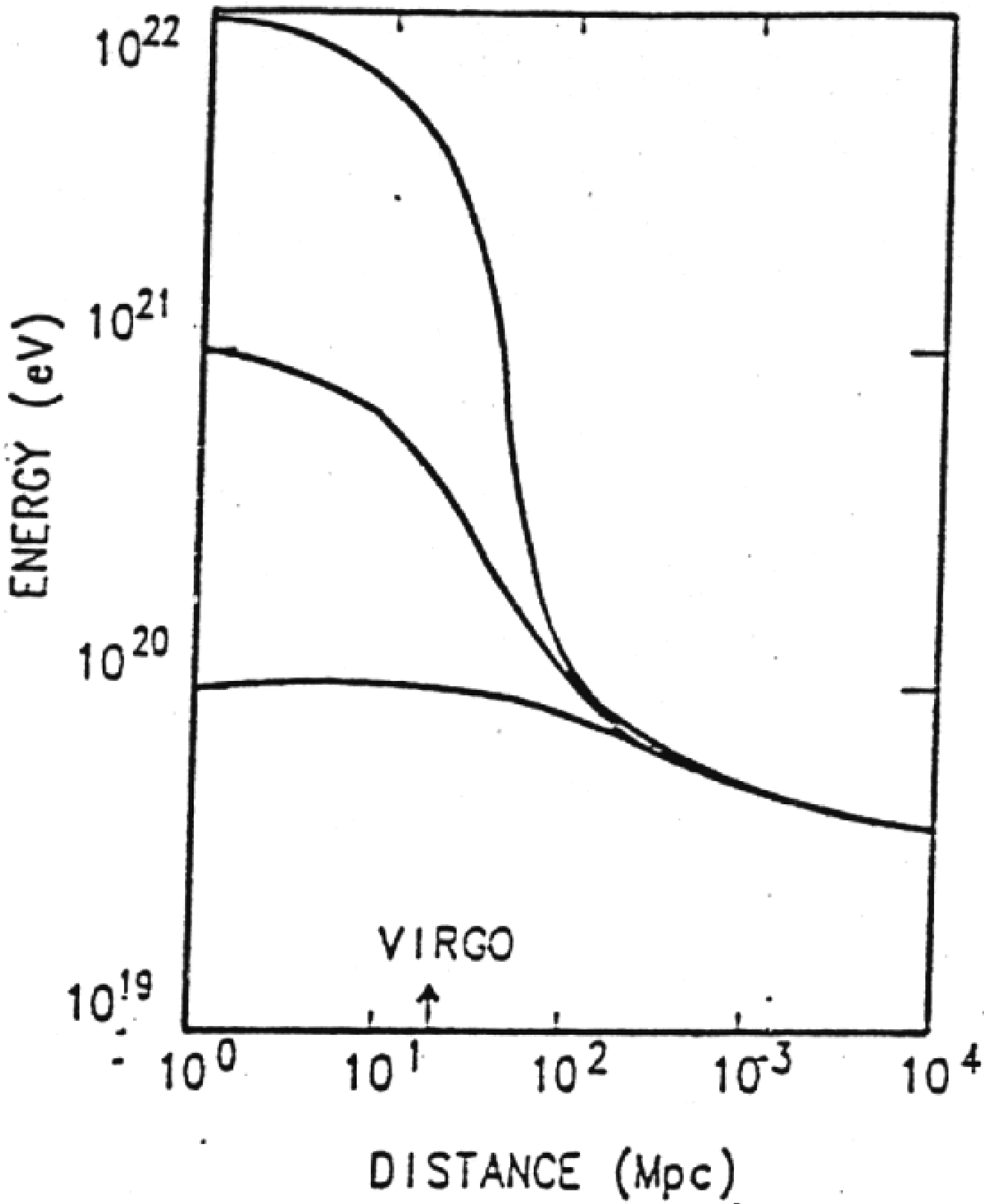

FIGURE 3. Calculated mean energy of protons due to the interaction with 2.7°K radiation as a function of distance for various initial energies.

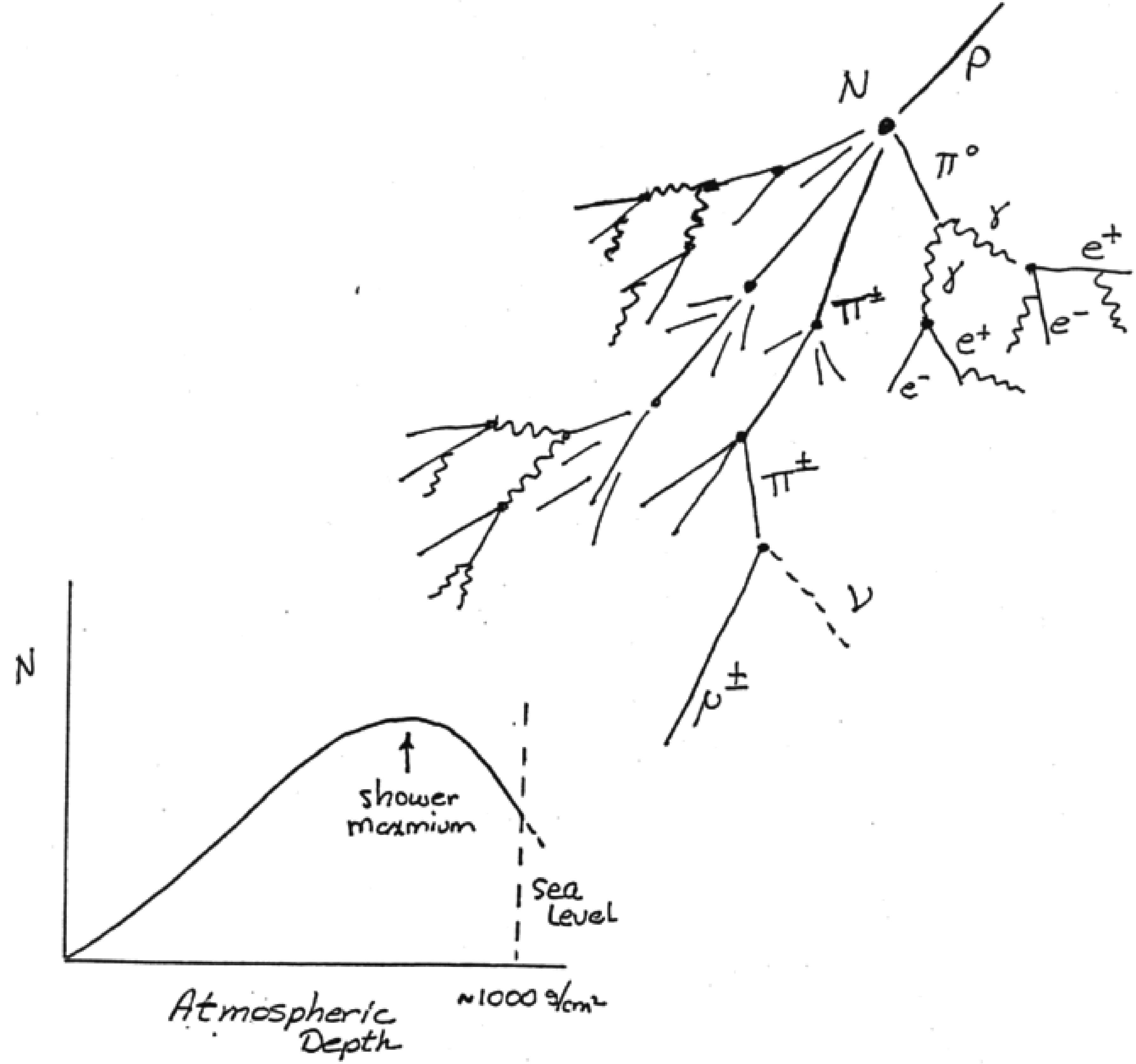

FIGURE 4. Longitudinal shower development.

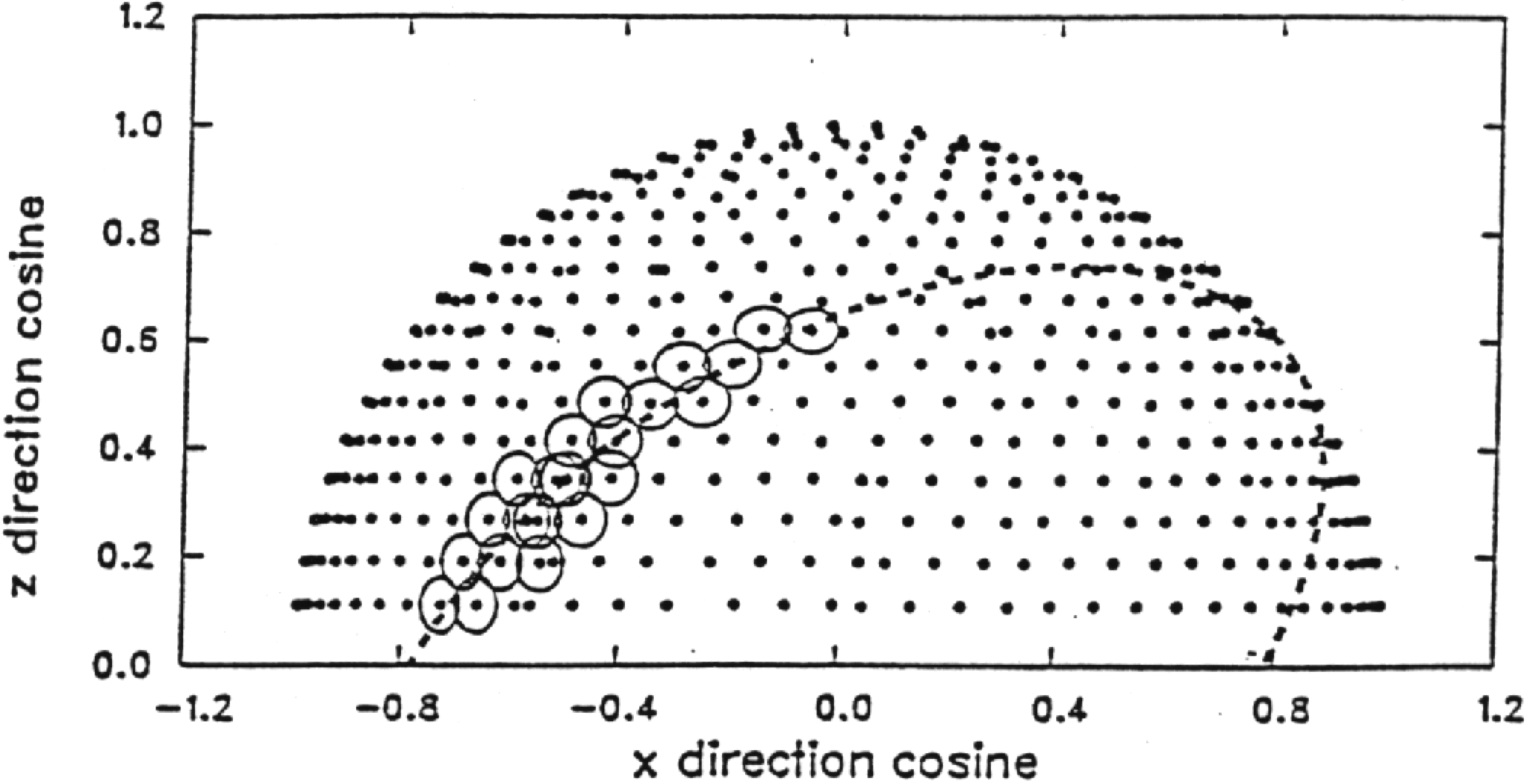

FIGURE 5. Pointing directions of Fly's Eye phototubes triggered by the $3.2 * 10^{20}$ eV shower.

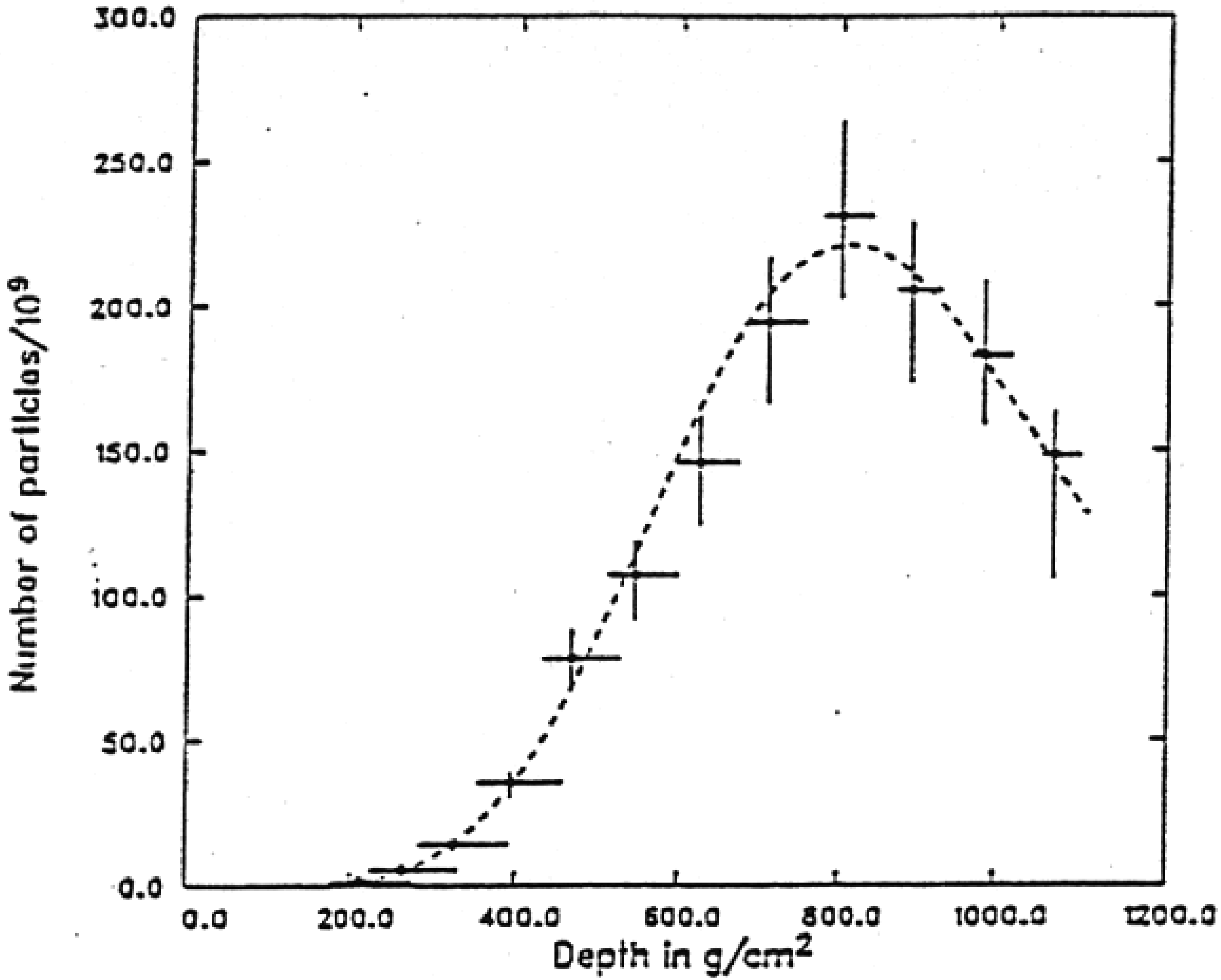

FIGURE 6. Shower profile for the $3.2{*}10^{20}$ eV Fly's Eye event.

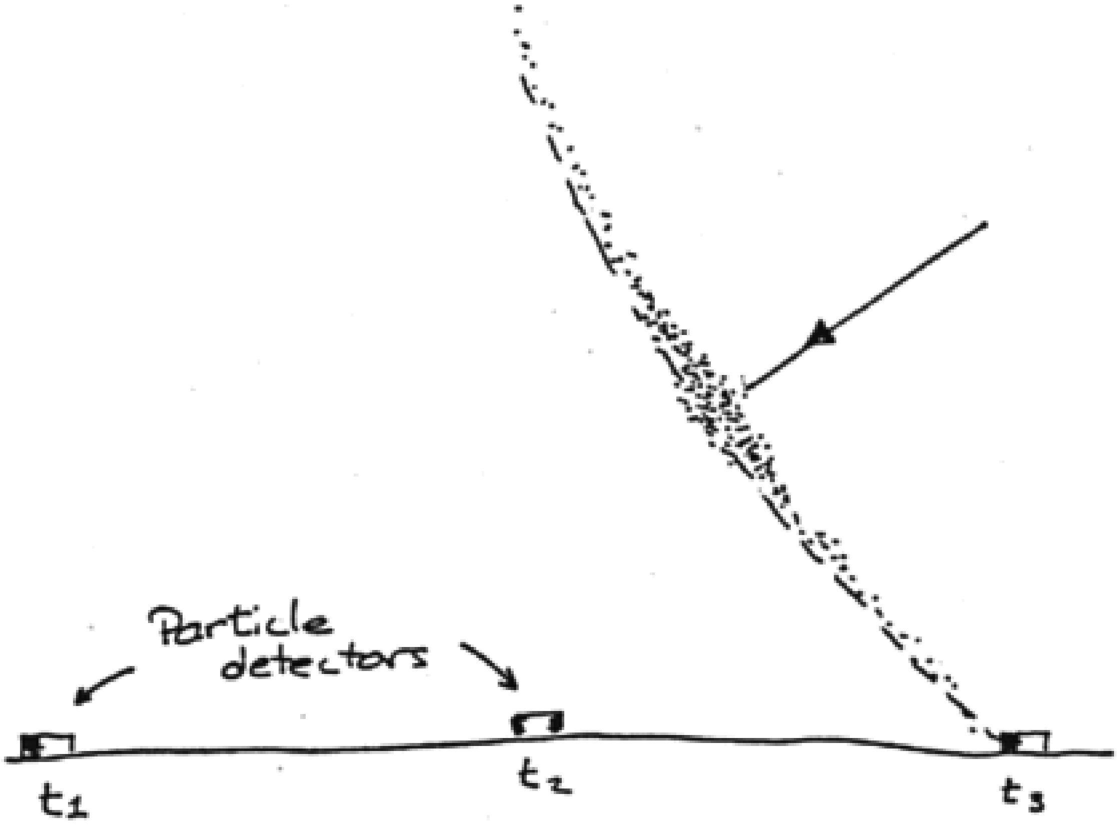

FIGURE 7. Illustration of cosmic ray direction measurement using air shower front.

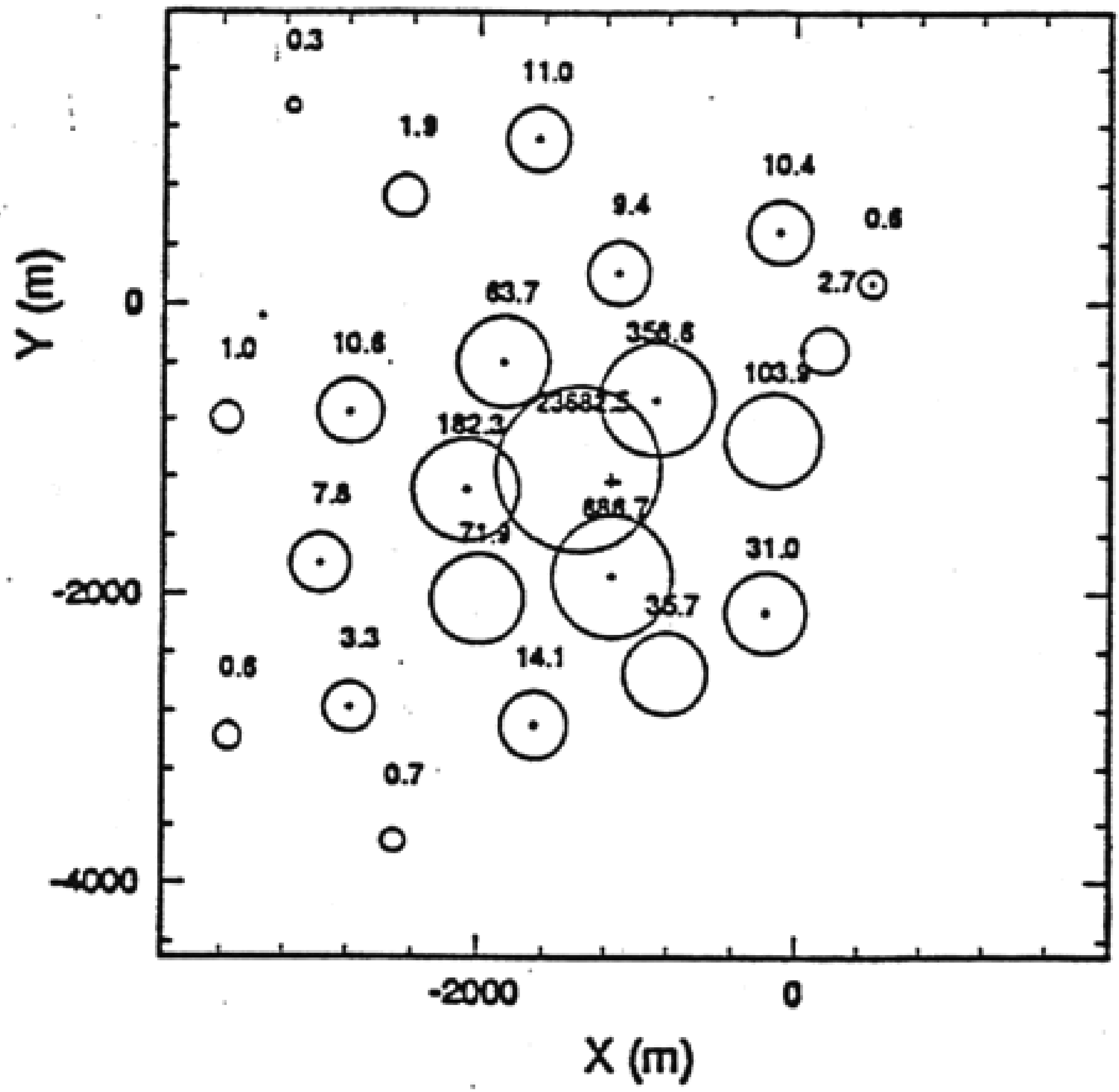

FIGURE 8. Map of the density distribution of the giant air shower observed by the AGASA group. Each dot corresponds to a particle detector. The size of the circle is proportional to the logarithm of the particle density at each detector.

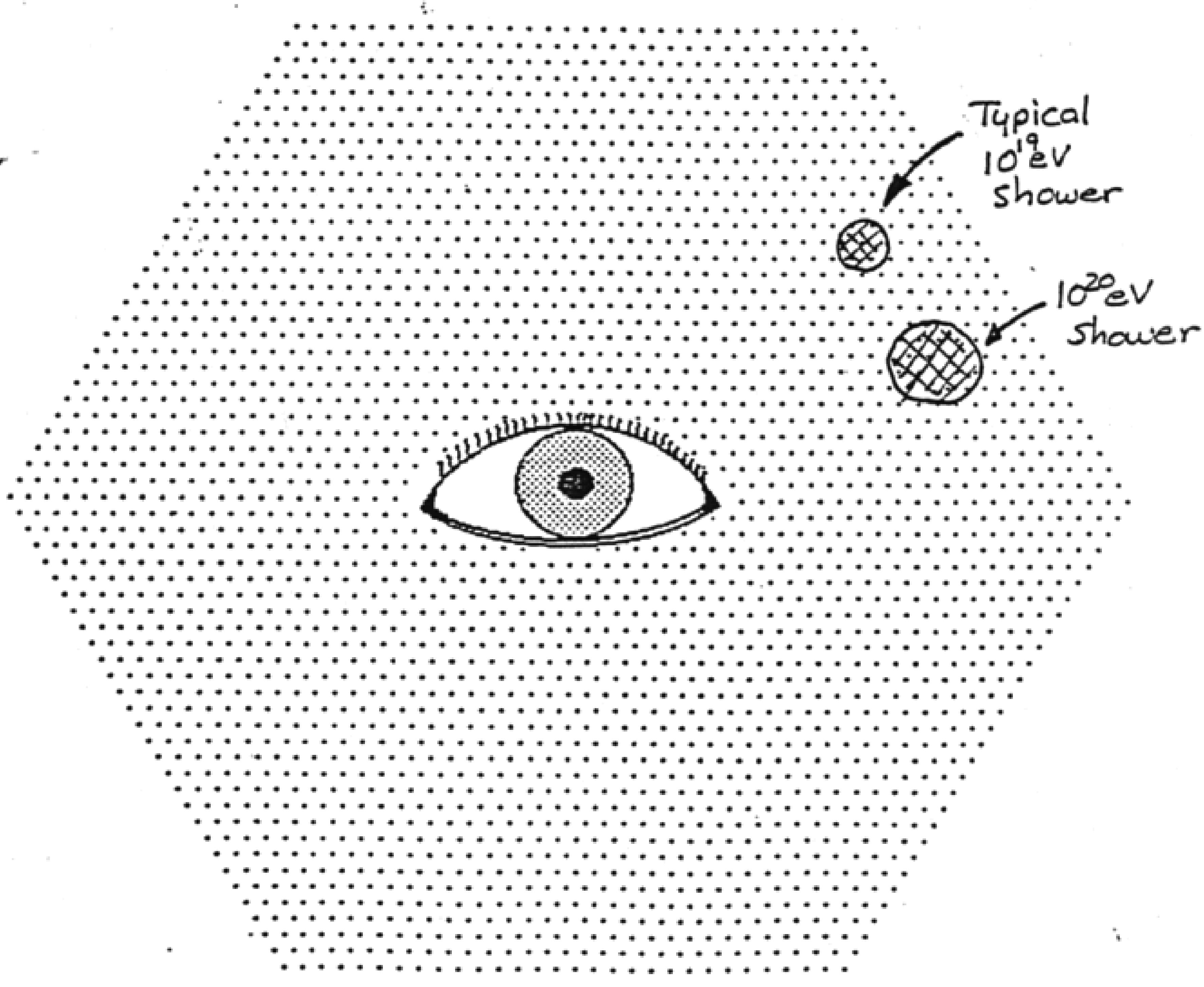

FIGURE 9. Cartoon of the ground array with fluorescence "eye" in the center. The circles are the approximate size of 10^{19} and 10^{20} eV showers.

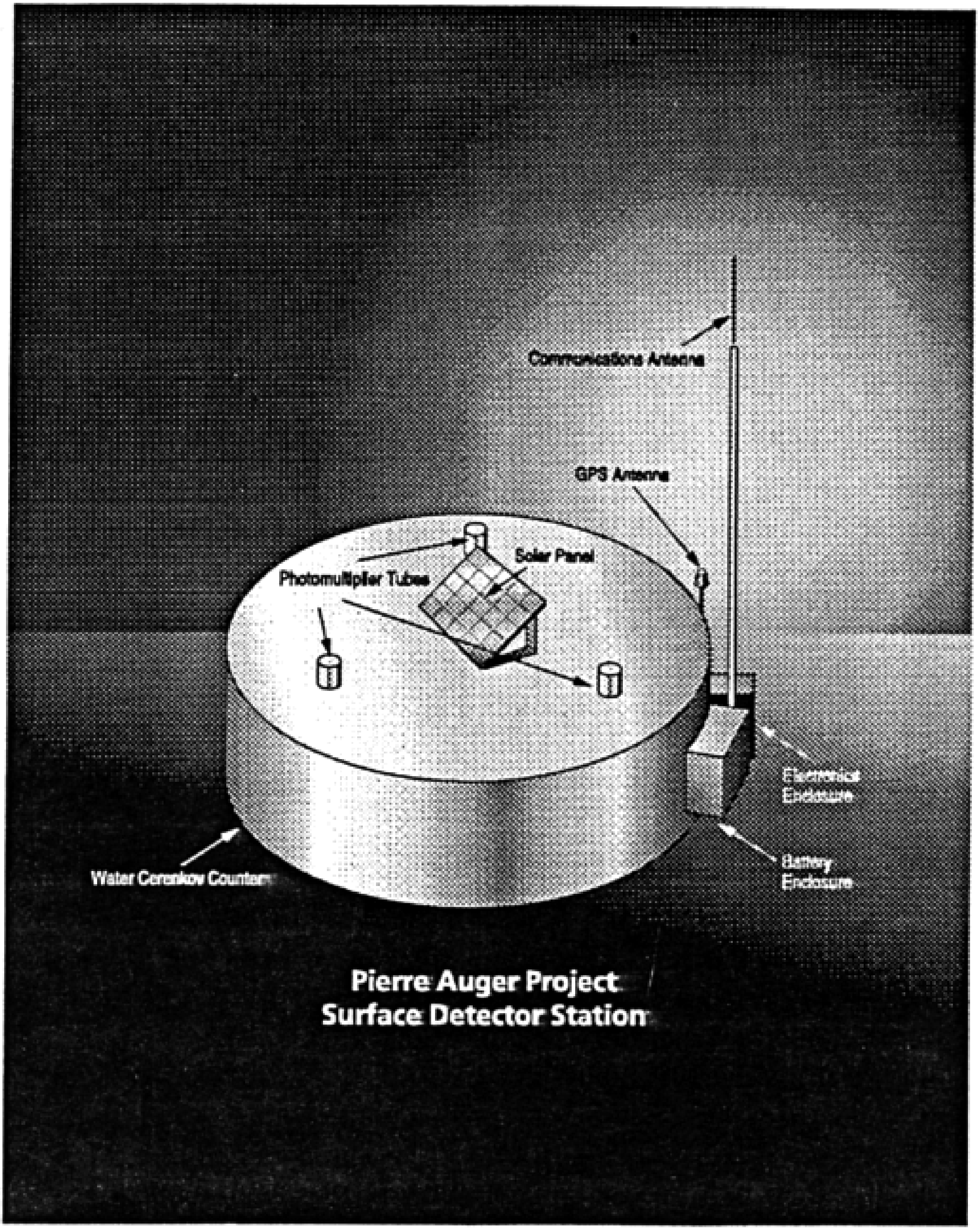

FIGURE 10. Conceptual design for the Water Cerenkov detector for use in the surface array.