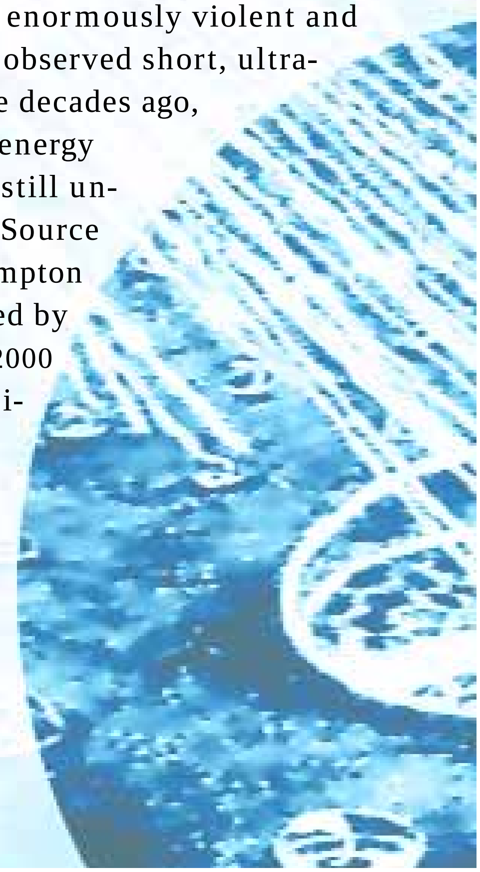
Capturing the Highest-Energy C

by PAUL MANTSCH

The highest-energy cosmic rays are the most energetic particles in nature yet their origin is unknown. These particles are so rare that to capture even a few, two huge arrays of detectors are proposed.

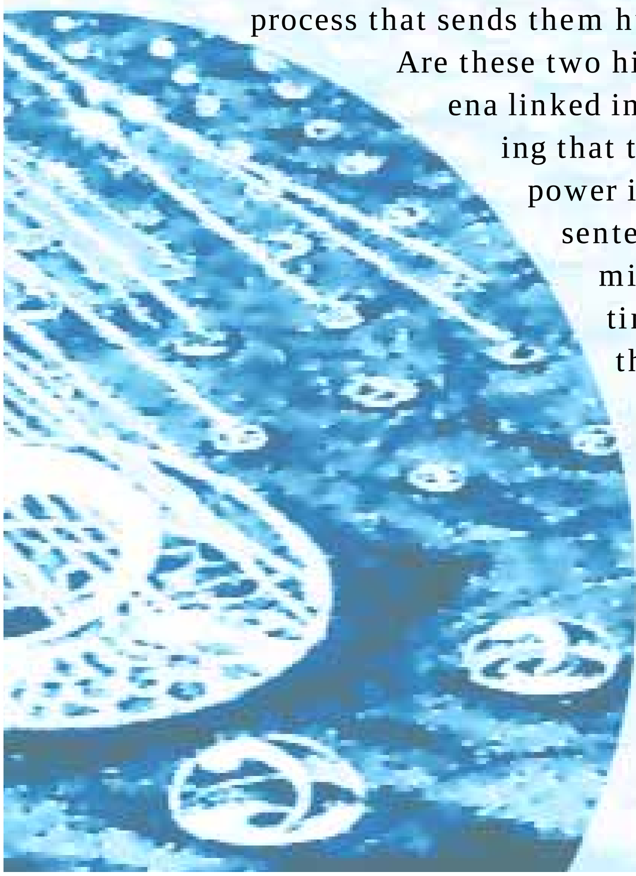
FOR STUDENTS OF THE COSMOS, these are extraordinary times. We live at a moment when scientific instruments of dazzling capability are flooding us with new data, teaching us more and more about the mysteries of the Universe, even as they raise fascinating questions about its secrets.

Of the cosmic enigmas that have emerged from the observations of recent years, two of the most intriguing concern the mysterious origins of two ultrahigh-energy phenomena that may or may not turn out to be related: gamma ray bursts and ultrahigh-energy cosmic rays. Both of these phenomena appear to come from enormously violent and powerful sources. Scientists first observed short, ultra-bright bursts of gamma rays three decades ago, but the explanation for the huge energy release they seem to represent is still unknown. The Burst and Transient Source Experiment (BATSE) aboard the Compton Gamma Ray Observatory launched by NASA in 1991 has recorded over 2000 gamma ray bursts, distributed uniformly over the sky. Although astrophysicists have made recent progress in associating a few gamma ray bursts with optical counterparts, the provenance of these enormously powerful events remains a conundrum.



smic Rays

The origin of the highest-energy cosmic rays poses another riddle. (Even the name "cosmic ray" has the ring of the mysterious cosmos; and, although the radiation continually raining down on earth has turned out to consist more of particles than of rays, the name "cosmic ray" has stuck.) Although they are very rare, the highest-energy cosmic rays are the most energetic particles in nature. Observers have recorded cosmic rays with a hundred million times more energy than the protons produced by Fermilab's Tevatron, the world's most powerful accelerator. Yet no one knows where these cosmic rays come from or what might be the violent process that sends them hurtling through space.



Are these two highest-energy phenomena linked in some way? It is striking that the total amount of power in the Universe represented by high-energy cosmic rays (averaged over time) is similar to that involved in gamma ray bursts. In solving scientific mysteries, we often look for related phenomena. Might their spectacular common energy level be a clue? One way to

Measuring Cosmic Ray Energies

SCIENTISTS TYPICALLY MEASURE the energy of very energetic particles using a variation of the classic calorimeter found in a freshman physics laboratory that consists of an insulated container of water with a thermometer. The student adds a known amount of mechanical energy to the water by stirring and measures the rise in the water temperature to find the heat energy added to the water. Calorimeters in particle physics measure energy by sampling the energy loss of a particle as it produces a cascade of particles in an absorbing material like lead or steel. The more energetic the particle, the thicker the absorber must be to contain all of its energy. Calorimeters at high-energy accelerator experiments usually consist of alternating layers of absorber and scintillating plastic. The size of the cascade—a measure of the energy of the incident particle—is determined by measuring the light produced in the scintillator, using photomultiplier tubes. Such calorimeters weigh thousands of tons. Yet the highest-energy cosmic rays have much more energy than accelerators produce. For cosmic rays of 10^{20} eV, indeed a large calorimeter is needed: the earth's atmosphere.

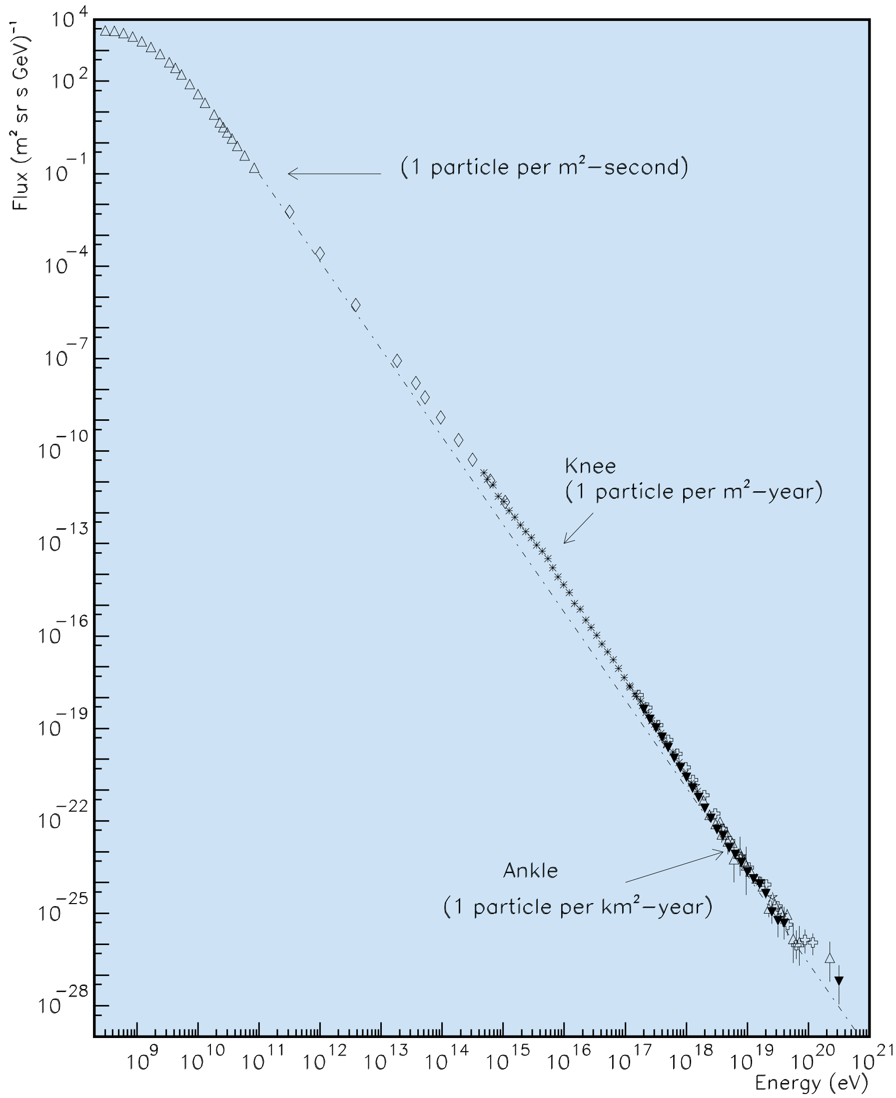
Of the two air shower detection methods, fluorescence detection provides a more direct measure of the primary particle's energy. The light due to ionization is a measure of the electromagnetic shower size and hence of the energy. For surface detectors, on the other hand, energy determination depends on comparison to simulated showers. Although the first few interactions of the shower depend on particle production models that extrapolate well above accelerator data, the particle densities on the ground are fairly insensitive to this process. Energy determination depends, therefore, on well-understood electromagnetic cascade processes involving millions of particles out to several kilometers from the core. Uncertainties arising from statistical sampling are negligible, because the shower sizes are so large. Rather, the fluctuations in shower development, mainly from variation in the depths of the first interaction, dominate. Studies by Michael Hillas have shown that these shower-to-shower fluctuations reach a minimum at about 600–800 m from the shower core. Measuring and fitting the lateral particle density distribution sampled by the detector array and comparing this to shower simulations yields an energy determination with a precision of 10 to 30 percent.

try to find out is to study the cosmic rays more closely.

In the past thirty years, observers have recorded ten cosmic ray events with energies at or above 10^{20} electron volts (eV). Recently, scientists have reported two events with energies well above 10^{20} eV. When high-energy cosmic rays hit the atmosphere, they collide with air atoms to create cascades, or air showers, of secondary particles. In 1991, the Fly's Eye Group in Utah, using an air fluorescence detector, observed an air shower with a measured energy of 3.2×10^{20} eV. In 1993, a group working at the AGASA array in Akeno, Japan, reported an event with an energy of 2.1×10^{20} eV.

We can account for the origins of garden-variety cosmic rays with energies up to about 10^{15} eV; we believe that they get their acceleration from the expanding shocks of supernovae. But it is very difficult to conceive of a method of acceleration that can account for the highest-energy cosmic rays. Where do they come from?

The mystery deepened when scientists realized that cosmic rays with energies near 10^{20} must be coming from a relatively nearby source, because of the nature of the cosmic soup they must travel through. In 1965, Arno Penzias and Robert W. Wilson discovered that space is permeated by microwave radiation left over from the birth of the Universe. Then Kenneth Greisen, Georgi Zatsepin, and Vadim Kuzmin independently showed that this radiation would make space opaque to cosmic rays of very high energy. To a high-energy proton, they reasoned, a collision with even a low-energy microwave photon would be energetic enough to produce pions. Successive pion-producing collisions would rob the proton of energy until it fell below the threshold for pion production and could continue on its way unaffected by the cosmic microwave background. The "Greisen-Zatsepin-Kuzmin cutoff" takes effect at proton energies greater than about 5×10^{19} eV. High-energy nuclei and photons experience similar energy degradation. Thus, cosmic rays with energies higher than the cutoff must come from close by, because they must arrive on Earth before traveling long energy-sapping distances. Scientists believe they must come from nearer than about 50 megaparsecs, or 150 million light years away. If Nature behaves the way we think it does, we should look for the sources of ultrahigh-energy cosmic rays in our own galactic neighborhood.



Observed energy spectrum of high-energy cosmic rays from different experiments. (Courtesy Simon Swordy, University of Chicago)

Ultrahigh-energy cosmic rays have another helpful feature. Magnetic fields that pervade the Milky Way galaxy and intergalactic space deflect the paths of charged particles. But the cosmic ray particles we are studying are so energetic that they experience very little deflection by these galactic magnetic fields.

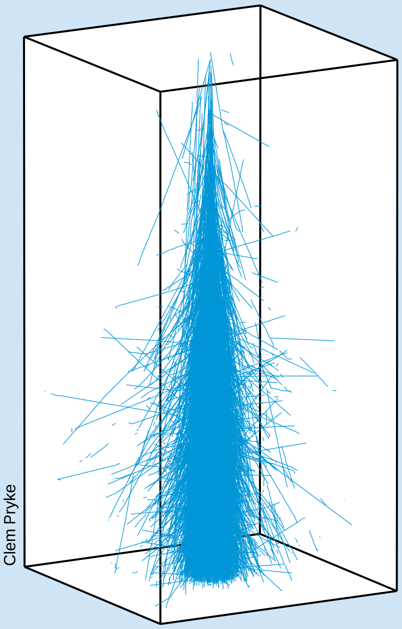
Thus, an ultrahigh-energy cosmic ray should come from close by, and it should point back toward its birthplace. It would seem that we could simply track back to possible cosmic ray sources and try to unravel the secret of their acceleration. Yet none of the high-energy cosmic rays observed so far points back to anything that looks remotely like a possible source! What are we missing? Is there some new physics or astrophysics at work? Here lies the mystery of the highest-energy cosmic rays.

Cosmic ray researchers face one daunting problem: the highest-energy cosmic rays they seek are extremely rare. The intensity of cosmic rays that strike the earth falls very rapidly with energy, as shown in the graph on the right. For every factor of ten increase in energy, the number of particles above that energy falls by a factor of 100. The most energetic cosmic rays have energies higher than 10^{19} eV—and only about one arrives on Earth per square kilometer per year. At 10^{20} eV, the number is down to one per square kilometer per century!

CAPTURING COSMIC RAYS

For the sources of gamma ray bursts, the satellite-borne BATSE is a beautiful instrument for scanning the sky. Gamma rays of a few tens of MeV can be captured and measured in the small detectors aboard the Compton Gamma Ray Observatory. Detecting the highest-energy cosmic rays is a different matter. It is utterly impractical to loft a big enough energy-measuring calorimeter into space to study a significant number of these rare and energetic particles. (See the sidebar on the facing page.) It would seem we can devise no BATSE equivalent for ultrahigh-energy cosmic rays—until we realize that Earth itself is our ready-made satellite and the earth's atmosphere makes an excellent calorimeter! Nature has built most of our detector for us. The atmosphere is just thick enough so that the air showers produced by incoming cosmic rays begin developing about 10 to 20 kilometers above the

Cosmic Ray Air Showers



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Visualize a cosmic ray air shower as a disk of particles moving down through the atmosphere at nearly light speed. It grows broader and more intense as it approaches the earth.

WHEN A HIGH-ENERGY COSMIC ray photon, proton, or nucleus hits an air molecule in the upper atmosphere, it produces a cascade of particles. At each generation of this cascade, a larger fraction of the energy is transferred from hadronic particles (mostly pions) to electrons and photons. The energy of the charged pions eventually degrades to the point where the pions are more likely to decay into muons than to interact. Thus, after a few generations, the cascade is nearly all electromagnetic with about one percent muons. Eventually, the electromagnetic cascade can no longer multiply and the shower begins to diminish as the particles lose the last of their energy, mostly by ionization. The maximum shower density occurs just above the earth's surface.

An air shower cascade becomes large and very intense. A shower started by a cosmic ray with 10^{20} eV builds up to a hundred billion particles and covers 20 square miles by the time it reaches the surface.

earth and reach their maximum intensity just above the earth's surface. (See the sidebar on the left.) The atmosphere is also nearly transparent to the faint fluorescent light produced as showers pass through the atmosphere. By placing an array of devices on the earth's surface, we can measure the energy and direction of the primary particle of the cosmic ray, and even gain information about its mass. If we place arrays in both the northern and southern hemispheres, the rotation of our "satellite" produces a uniform scan of the whole sky.

MEASURING AIR SHOWERS

The most commonly used methods for air shower measurement are those that detect atmospheric fluorescence and those that measure particle densities on the earth's surface. On dark, moonless nights, nitrogen fluorescence produced by air shower-induced ionization can be detected by an array of photomultiplier tubes trained on the sky. The Fly's Eye group at the University of Utah pioneered this elegant method, which observes the shower as a spot of light moving across the sky. By measuring the intensity of light and the timing of the photons, the Fly's Eye can directly measure the energy deposition profile of the air shower. Since dark, clear nights are required, fluorescence detectors can be active about ten percent of the time. The Cerenkov technique used to detect high-energy gamma rays as described in the following article by Gaurang Yodh requires the observer to be looking back at the source beams. The Cerenkov radiation is emitted only in the direction of the shower whereas fluorescence is emitted in all directions.

Particle detectors in a sparse array on the ground are the more traditional method of air shower detection. The particles in a shower propagate through the atmosphere at the velocity of light in the form of a thin disk perpendicular to the direction of the incident particle. The timing of the particles as they strike successive detectors in the array can be used to determine the direction of the shower and of the primary particle to about one degree. (See the illustration on the next page.) The well-understood electromagnetic cascade process involves millions of particles out to several kilometers from the shower core. Observers can use the measured particle density profile to calculate the primary particle energy. From the number of muons, the shape of the shower front and the rise time of the pulse in the particle detectors, observers can calculate the particle's mass. Measurements made by fluorescence detectors and ground arrays agree remarkably well. The high-energy spectra measured by the two methods agree to within about 20 percent.

HISTORY OF AIR SHOWER DETECTORS

In the 1960s, a team headed by physicist John Linsley performed beautiful pioneering experiments to measure ultrahigh-energy cosmic rays. Linsley's detector consisted of plastic scintillator counters spread over seven square kilometers of New Mexico at Volcano Ranch. He is credited with publishing the first event with an energy of 10^{20} eV in 1963. More recent ground arrays include one covering 12 square kilometers at Haverah Park in England, another covering 25 square kilometers at Yakutsk in Russia, and finally a 100-square-kilometer array in Akeno, Japan. Experimenters at Dugway Proving Ground in Utah are now using an enhanced version of the original Fly's Eye fluorescence detector. The new High Resolution Fly's Eye, which will have a time-averaged aperture of 1000 km^2 steradian, will start taking data in about a year.

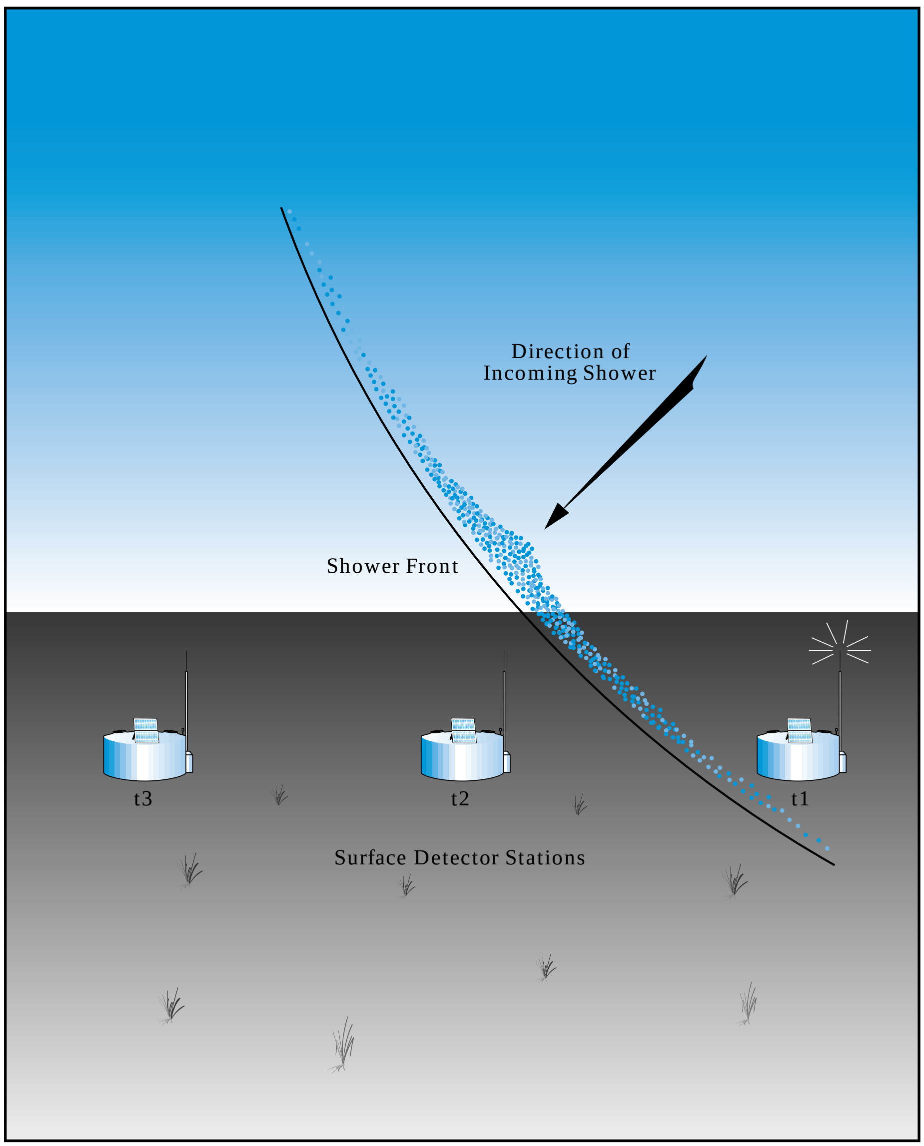
THE PIERRE AUGER PROJECT

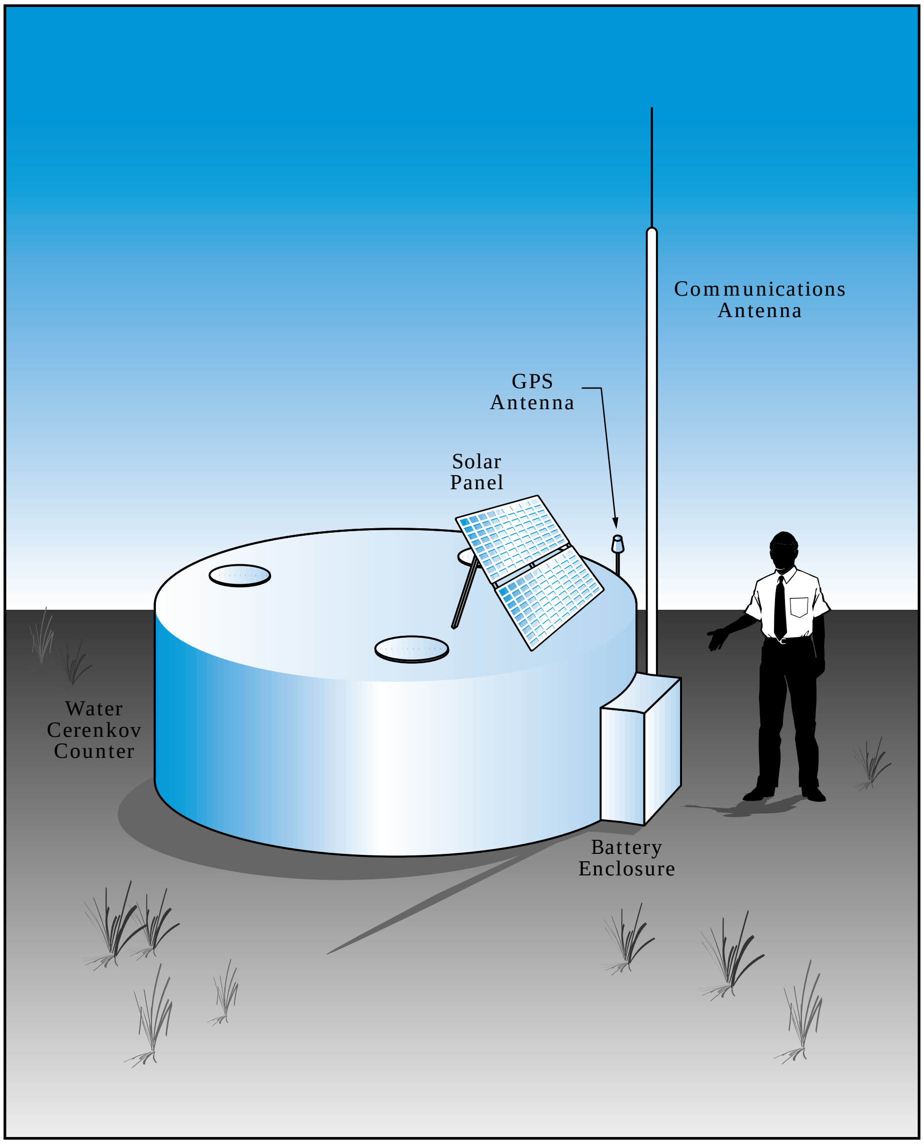
The Pierre Auger Project was born in a series of workshops, led by James Cronin of the University of Chicago and Alan Watson of the University of Leeds, in Paris (1992), Adelaide (1993), and at Fermi National Accelerator Laboratory in 1995. In October 1995, the workshops produced a reference design and a cost estimate for a proposed cosmic ray detector. Since then, the Pierre Auger collaboration has chosen observatory sites in Mendoza Province, Argentina, and Millard County, Utah.

The Auger Project's goal is a high-statistics study of cosmic rays in the range 10^{19} to 10^{21} eV, with uniform sky coverage using identical detectors in the earth's two hemispheres. The Pierre Auger Observatory will design and build a powerful, very large-aperture cosmic ray air shower detector at each site combining the strengths of atmospheric fluorescence and surface particle detectors. A surface array at each site will contain 1600 detector stations spread over 3000 square kilometers. This cost-effective array of detectors will be continuously "on," to gather high statistics. Fluorescence detectors patterned after those of the High Resolution Fly's Eye will view showers that strike the ground during dark periods.

Each observatory site will have several sky fluorescence detector stations to record showers that fall on the surface array. Each fluorescence

The cosmic ray air shower is a disk of particles moving through the atmosphere at nearly the speed of light. By recording the time as particles hit successive detectors, physicists can determine the direction of the incoming cosmic rays.





Pierre Auger surface detector station containing 12 tons of water and three photomultiplier tubes.

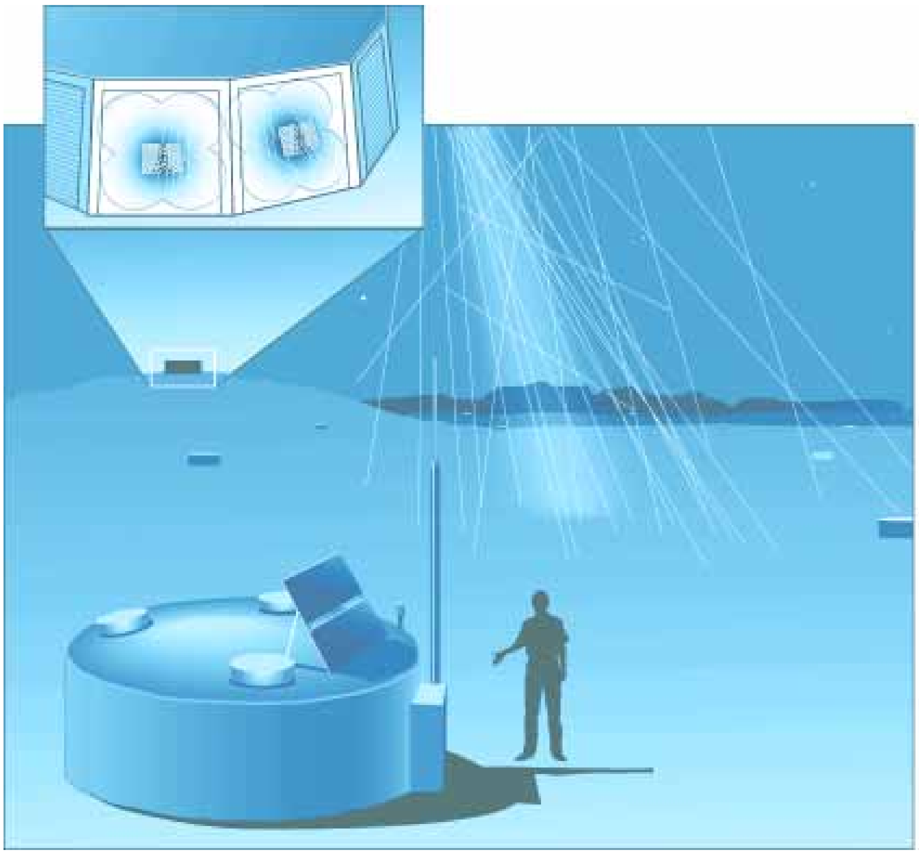
station will contain about 48 reflector telescope units, each with a four-meter-diameter mirror that focuses light from the sky on an array of a hundred photomultiplier tubes. Enclosures will shelter the fluorescence detectors from the daytime sun and the desert's harsh environment.

The Auger Observatory's surface detectors are water Cerenkov detectors, inspired by those that have operated reliably for over twenty years at Haverah Park. Each Auger station is a cylindrical water tank 3.7 m in diameter and 1.2 m high, holding 11,000 liters (3000 gallons) of filtered, deionized water (see drawing on the left). Three 8-inch photomultiplier tubes capture the Cerenkov light from particles passing into the tank. Water detectors are simple and robust, a must for the remote and harsh desert. Water Cerenkov detectors are sensitive to muons, photons, and electrons and, because of their height, they are uniformly sensitive to particles arriving almost horizontally. And last, the water tanks can be painted in colors that blend with surroundings—they look like livestock watering tanks.

Solar panels provide the electrical needs of each station. A radio transceiver provides communication with a central data station. A Global Positioning Satellite receiver on each station measures event timing to about 10 nanoseconds between tanks, with an absolute time measurement to 50 nanoseconds. A large pulse in one detector spread out in time is evidence for a shower in the surface array. The detector station alerts a central station, which then looks for similar signals from neighboring stations. A trigger signal from at least five stations defines an interesting shower, and the central station stores the information from the tanks for analysis.

During the times when both fluorescence and surface array detectors are active (the hybrid mode) the fluorescence detector will make a calorimetric energy measurement and will record the longitudinal shower development. The proposed hybrid detector has important advantages over either of its components used alone. In the hybrid mode, each detector can make an independent measurement of the cosmic ray particle energy, direction, and composition. The hybrid mode will control systematic errors inherent in either method alone. The particle density at the surface provides an energy correction for the part of the shower not visible to the fluorescence detector. The two techniques also measure the mass of the cosmic ray particle in complementary ways. Fluorescence detectors estimate the mass by measuring the depth of shower maximum, while surface detectors measure the muon rise time and muon-to-electromagnetic ratio, which is also related to cosmic ray mass. The energy measurement by the hybrid detector will calibrate the energy measurement of the surface array operating alone, as it will be doing about 90 percent of the time.

True mysteries in science are not so commonplace, and when we do come upon them, they are a great blessing. For solving such mysteries is almost certain to bring us to a new and more profound understanding of the nature of our Universe. If the Pierre Auger Project proceeds as its international collaborators hope, construction will begin at the southern site in 1999. About three years later, the first ultrahigh-energy cosmic rays will light up the detectors, inaugurating a powerful new probe for solving the mystery of their origin.



The Auger air shower detector system. The inset shows one of the concepts for the fluorescence detectors.

For readers wishing to pursue very high-energy cosmic rays in greater detail, the following URLs may be helpful:

HiRes http://sunshine.chpc.utah.edu/research/cosmic/hires/index.htm
AGASA http://www.icrr.u-tokyo.ac.jp/as/project/agasa.html
Auger http://www.auger.org