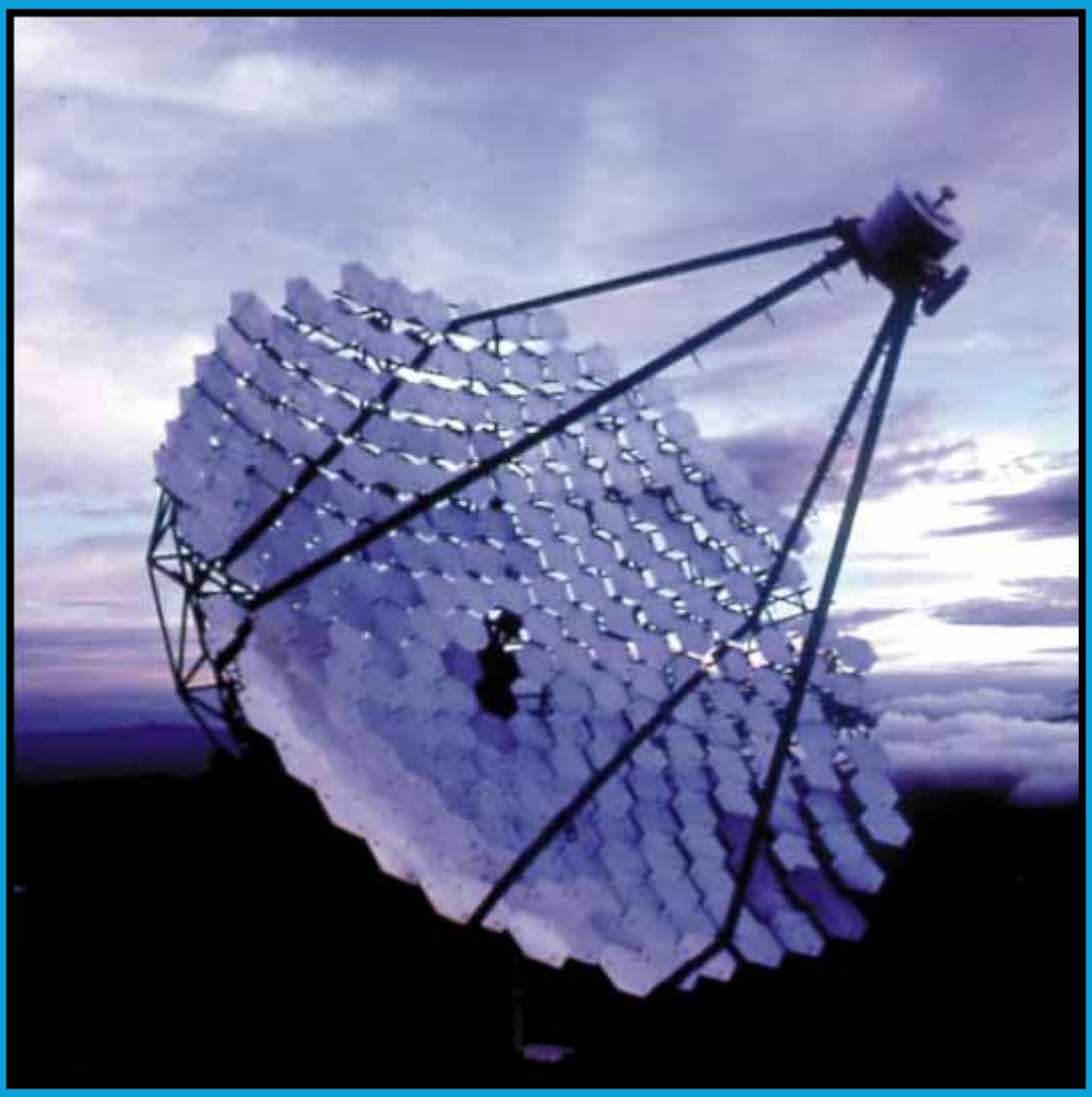
Beam Line

Fall/Winter 1998, Vol. 28, No. 3



Beam Line

A PERIODICAL OF PARTICLE PHYSICS

FALL/WINTER 1998 VOL. 28, NUMBER 3

The *Beam Line* is published quarterly by the Stanford Linear Accelerator Center, Box 4349, Stanford, CA 94309.
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Issues of the *Beam Line* are accessible electronically on the World Wide Web at http://www.slac.stanford.edu/ pubs/beamline.
SLAC is operated by Stanford University under contract with the U.S. Department of Energy.
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Cover: The 10-meter optical reflector at the Whipple Observatory, Mt. Hopkins, Arizona, at dusk. Faint glints can be seen from the 1.5-meter searchlight mirrors that serve as auxiliary reflectors.
(Courtesy Whipple Observatory, Smithsonian Institution)

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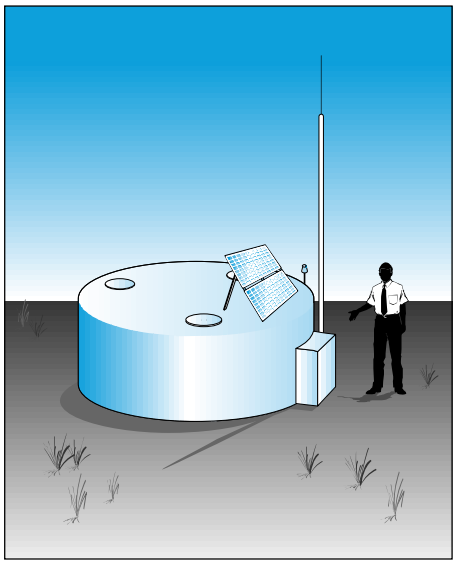

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FOREWORD

EVERY FEW SECONDS, a subatomic particle with the kinetic energy of a well-thrown baseball (approximately 10^{20} electron volts) strikes somewhere in the earth's upper atmosphere, unleashing a magnificent cascade of up to one hundred billion particles over an area of several square miles. Unfortunately, the show is over in a few nanoseconds, and most of the time no one is there to watch it. It is a shame to miss not only the fireworks, but also the chance to learn about the particle's birthplace. Clearly, this must be in some extreme environment, for instance near a supermassive black hole at the center of an active galaxy, but we don't really know where. Another mystery stems from the prediction (by Greisen, Zatsepin, and Kuzmin) that cosmic ray protons above about 10^{20} eV should be rapidly degraded by interactions with the cosmic microwave background, yet no falloff has been seen to date.

The trajectories of cosmic rays of such tremendous energies are bent very little by galactic magnetic fields, so that with more than the present handful of observed events one could begin to "do astronomy" by identifying individual sources on the sky. In this issue of the *Beam Line*, Paul Mantsch describes the two techniques that have been used to detect the highest-energy cosmic rays: giant air shower arrays that sample the debris of the cascade once it reaches the ground, and telescopes that capture the distant flash of fluorescing air molecules excited by the ionizing radiation. He also gives an overview of the Pierre Auger Project (named after an early pioneer in cosmic ray physics), which plans in the next few years to combine both approaches and provide us with our best clues to the origin of these particles.

As Gaurang Yodh points out in the second article in this issue, gamma rays, being neutral, also point back to their birthplace, and at TeV energies their air showers can be detected by related techniques. (Detection of Cerenkov radiation supplants the fluorescence approach in this case.) The challenge in high-energy gamma ray astronomy is to suppress the much more copious charged particles of the same energy. But this can be done, and TeV gamma rays have

been traced back to at least a couple of active galaxies. Several new detectors are in the works in this field as well.

Virginia Trimble puts this extraterrestrial high-energy frontier into perspective in her usual inimitable style. Finally, we return to Earth for Reinhard Brinkmann's description of a proposed accelerator at the terrestrial high-energy frontier: the TESLA superconducting linear collider.

In the Winter 1997 issue of the *Beam Line* (Vol. 27, No. 4), we announced three new contributing editors: Gordon Fraser from CERN; Judy Jackson from Fermilab; and Pedro Waloschek from DESY. These talented people have already helped us by authoring, editing, and alerting us to interesting articles in particle physics. With their help we have America and Europe pretty well covered, but we have been missing a contributing editor from Asia. Accordingly, Akihiro Maki from the National Laboratory for High Energy Physics (KEK) in Tsukuba, Japan will fill that role. Maki joined KEK in 1972 right after its establishment to build the first proton synchrotron in Japan. During his 26 year career there he has worked on experiments at Fermilab and Rutherford Laboratory, in addition to ones at KEK. He served as the director of the Washington Liaison Office of the Japan Society for the Promotion of Science (JSPS) to promote academic collaboration and exchange of researchers between the United States and Japan. He has since returned to KEK, and we are pleased to have him as a contributing editor.

Akihiro Maki at the Gastown Steam Clock, Vancouver, British Columbia, July 1998

Lance Dixon

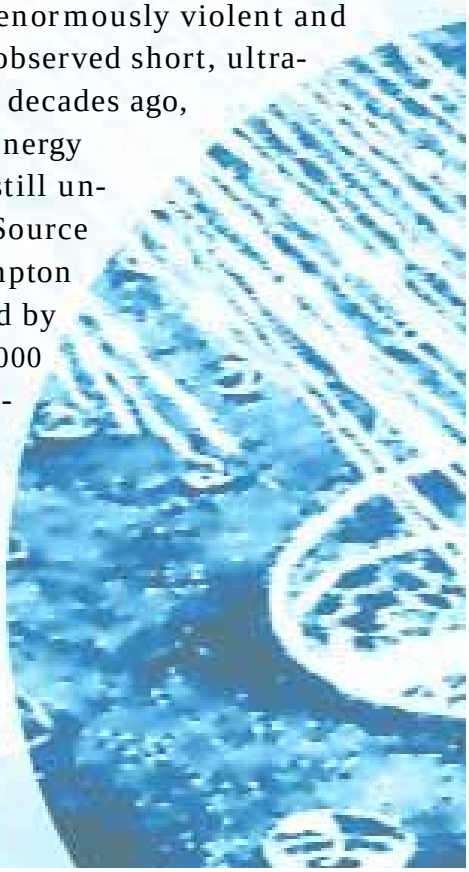
Capturing the Highest-Energy C

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.

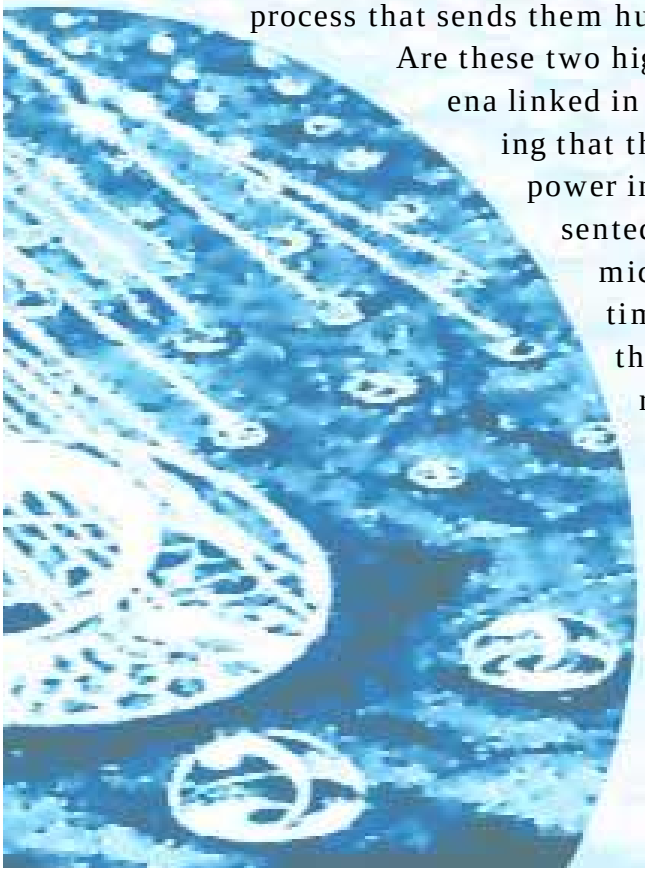
FOR STUDENTS OF THE COSMOS, these are extraordinary times. We live at a moment when scientific instruments of dazzling capability are flooding us with new data, teaching us more and more about the mysteries of the Universe, even as they raise fascinating questions about its secrets.

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, ultrabright 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.

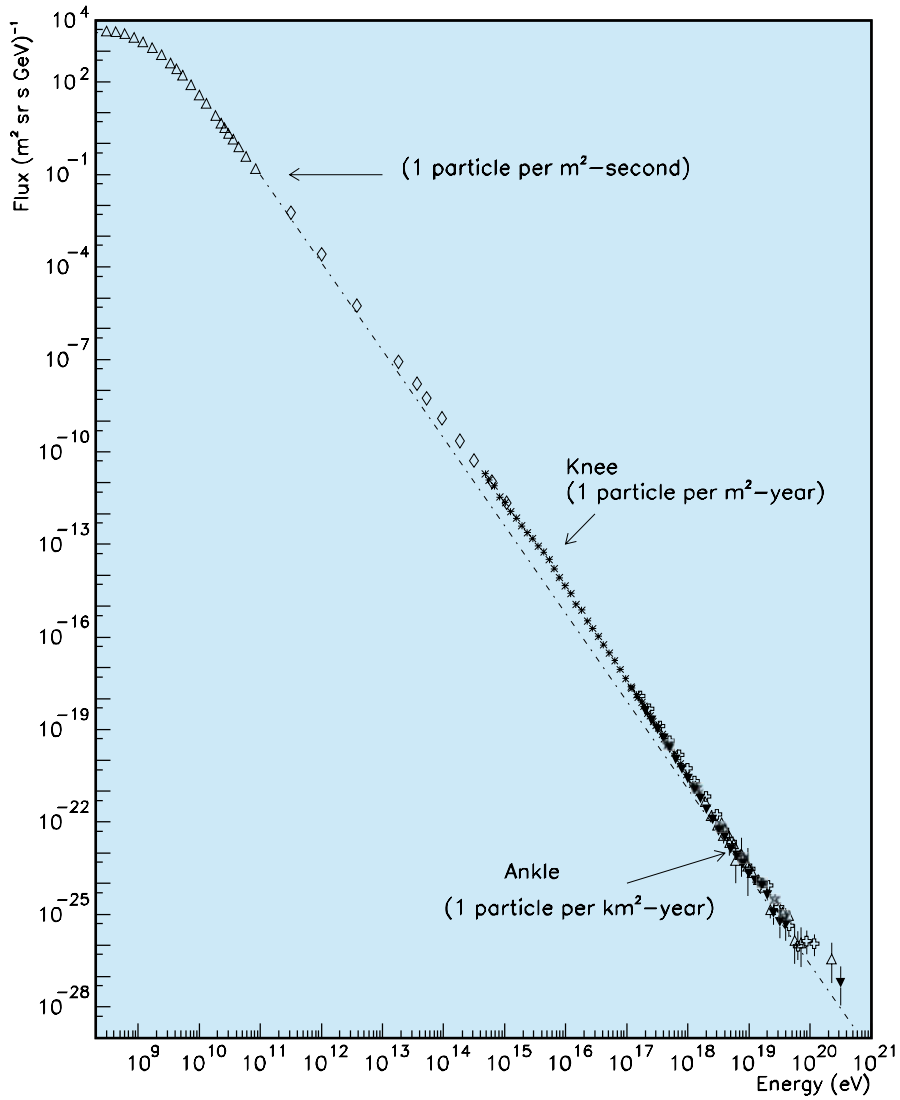
We can account for the origins of garden-variety cosmic rays with energies up to about 10^{15} eV; we believe that they get their acceleration from the expanding shocks of supernovae. But it is very difficult to conceive of a method of acceleration that can account for the highest-energy cosmic rays.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

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!

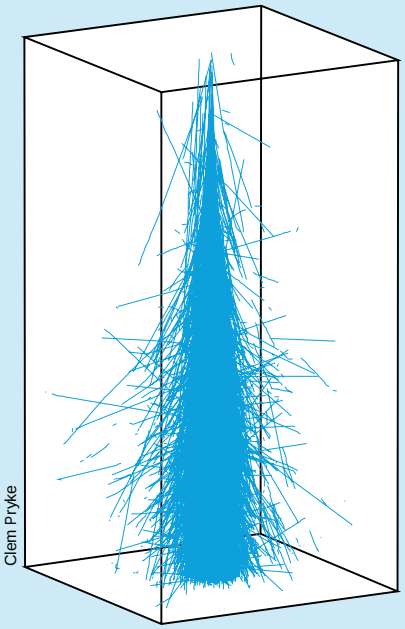


Observed energy spectrum of high-energy cosmic rays from different experiments. (Courtesy Simon Swordy, University of Chicago)

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



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.

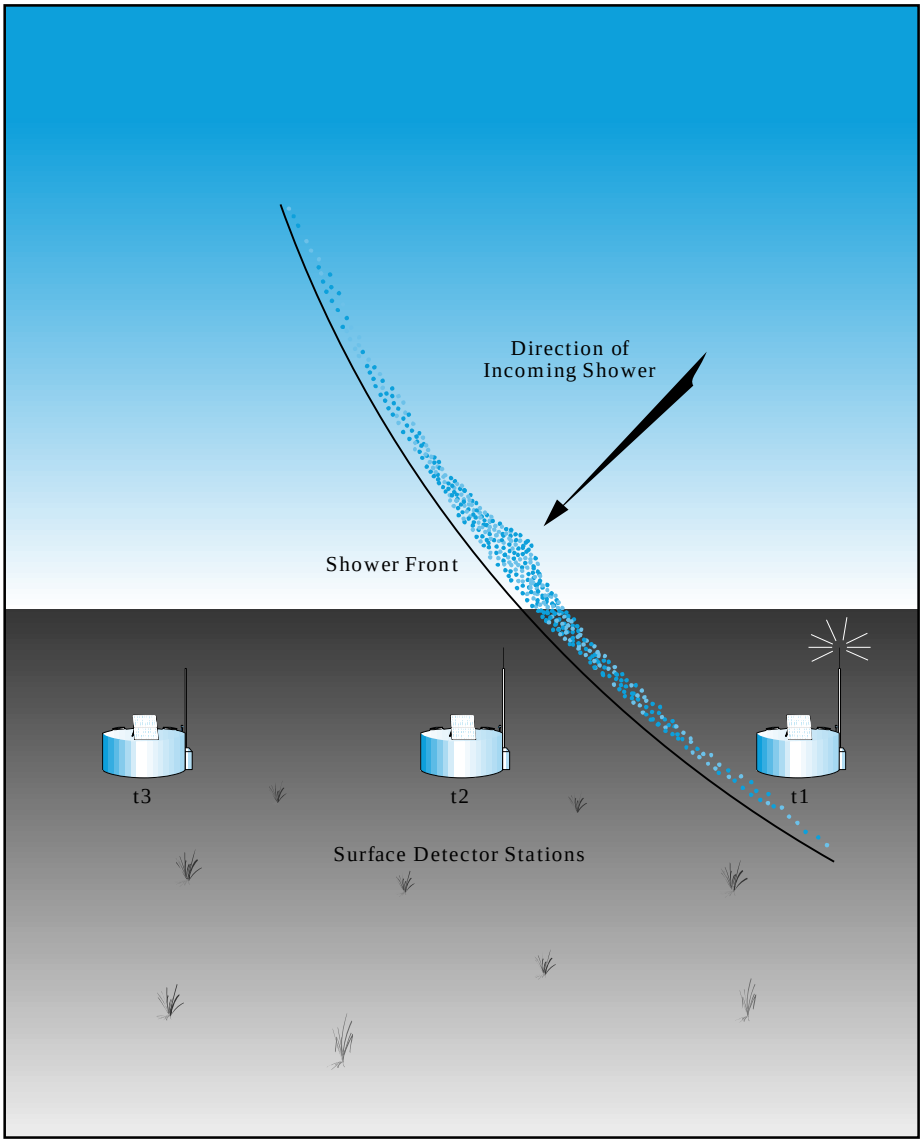
THE PIERRE AUGER PROJECT

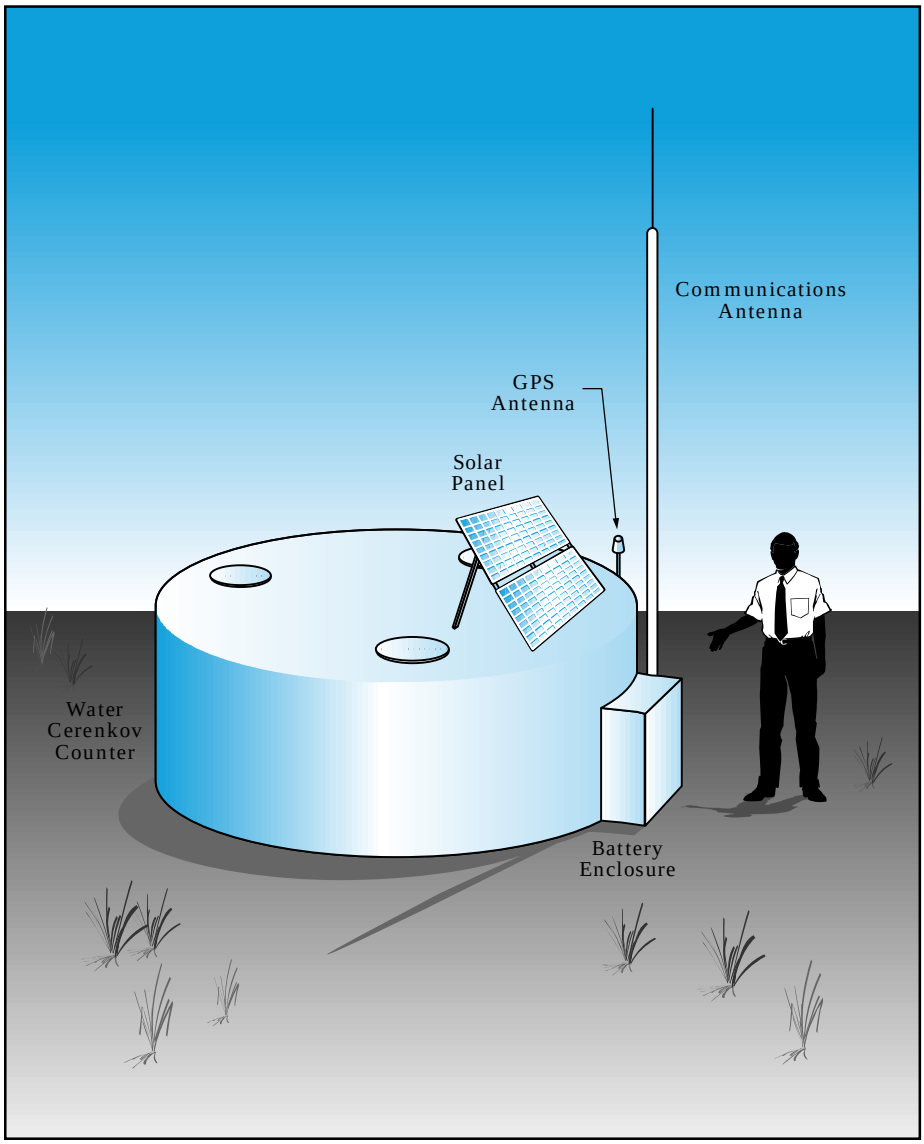
The Pierre Auger Project was born in a series of workshops, led by James Cronin of the University of Chicago and Alan Watson of the University of Leeds, in Paris (1992), Adelaide (1993), and at Fermi National Accelerator Laboratory in 1995. In October 1995, the workshops produced a reference design and 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.

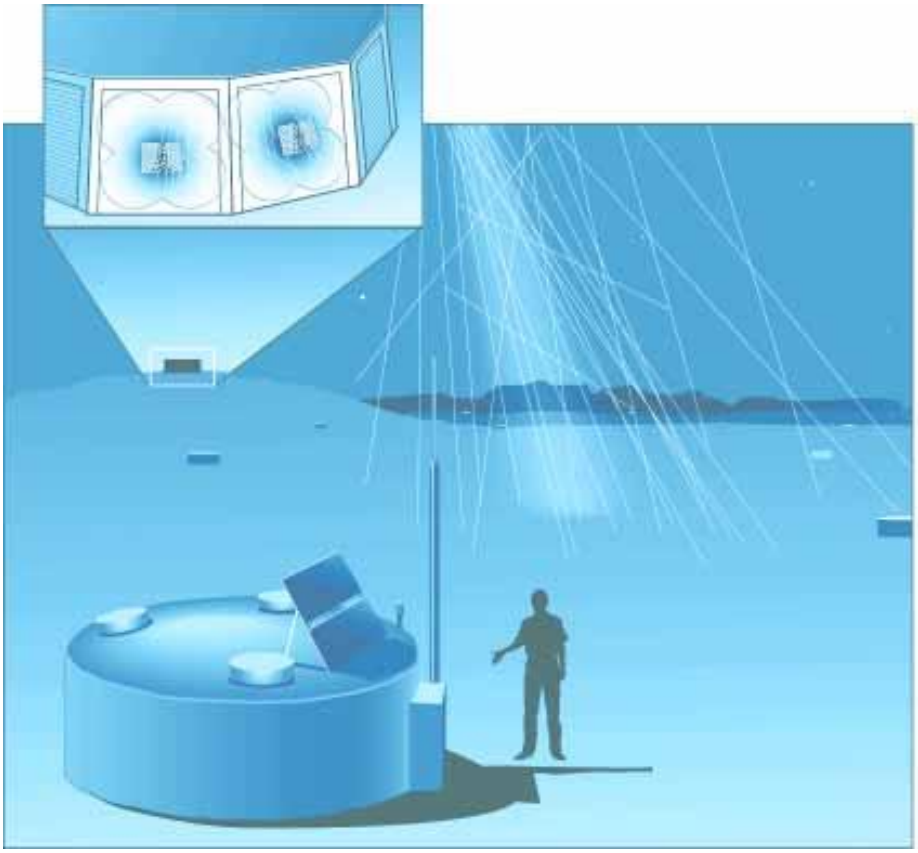
The Auger Observatory's surface detectors are water Cerenkov detectors, inspired by those that have operated reliably for over twenty years at Haverah Park. Each Auger station is a cylindrical water tank 3.7 m in diameter and 1.2 m high, holding 11,000 liters (3000 gallons) of filtered, deionized water (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

Very High-Energy Gamma Ray

by GAURANG B. YODH

THE VERY HIGH-ENERGY GAMMA RAY WINDOW ON THE UNIVERSE

A new generation of gamma ray telescopes being built throughout the world using air Cerenkov and air shower techniques will be able to detect rare, very high-energy gamma rays from distant celestial sources, thus enhancing our understanding of cataclysmic astrophysical events.

THE EARTH IS CONTINUOUSLY BOMBARDED by cosmic rays whose energy spectrum extends from a few GeV to 10^{11} GeV. After almost eighty years, since the discovery of cosmic radiation by Hess in 1912, the origin of cosmic rays is still not well understood. Understanding the nonthermal processes and the environments that generate these high-energy particles is a fundamental problem in astrophysics. Gamma rays produced by the energetic collisions of particle beams in these sources can be rare messengers that provide important clues to understanding these energetic electromagnetic and nuclear processes. In this view, the sources of gamma rays of energies above about 100 GeV must be beams of charged particles that have been accelerated to still higher energies. Some of the possible sources for energetic gamma ray production include jets emerging from active galactic nuclei, the catastrophic collisions that seem to be responsible for gamma ray bursts, special radio galaxies, and the environments of rapidly spinning neutron stars or supernova remnants. Even more exotic sources for these energetic gamma rays have been proposed, such as the annihilation of weakly interacting massive particles producing monochromatic gamma rays, and also the decay of cosmic strings left over from the Big Bang.

Very high-energy (VHE) gamma ray astronomy is the observational science of measuring their flux, point of origin, energy spectra and temporal variations. These measurements provide the test bed for theoretical models of the astrophysical sources generating high energy particle beams, the nature of the medium in which they generate the gamma rays, and the

properties of the background photons that can modify the source spectra of gamma rays during their transit to Earth. Specifically, VHE refers to energies above a few hundred GeV, which corresponds to wavelengths smaller than about 6×10^{-9} nanometers. The telescopes that are used to study VHE gamma rays have to be sensitive to very small fluxes, typically 6×10^{-4} photons per square meter per hour. Considerable ingenuity is thus needed in designing telescopes to achieve believable detection of this very small flux.

It is particularly important at the outset to emphasize a fundamental difference between particle showers that are initiated by gamma rays and those initiated by cosmic rays (mostly protons). Protons and other electrically charged particles have their motion affected by galactic and intergalactic magnetic fields, which means that their arrival direction on Earth does not "point back" toward their source. This is not the case with the electrically neutral photons of gamma radiation, for which arrival direction does in fact correlate with source direction.

Since about 1987, VHE astronomy has achieved the status of credible observational science with the unambiguous detection of two galactic and two extragalactic sources in the few hundred GeV to few TeV energy range by the atmospheric (or air) Cerenkov telescope (ACT) technique. These observations have provided excellent challenges to theoretical modelers of these sources.

Typical energetic extragalactic sources observed by air Cerenkov telescopes are the two active galactic nuclei (AGN) blazars Markarian (Mrk) 421 and Mrk 501. Mrk 421 is at a distance of about 120 Mpc; its intrinsic luminosity in TeV gamma rays, if it is all beamed into a solid angle of

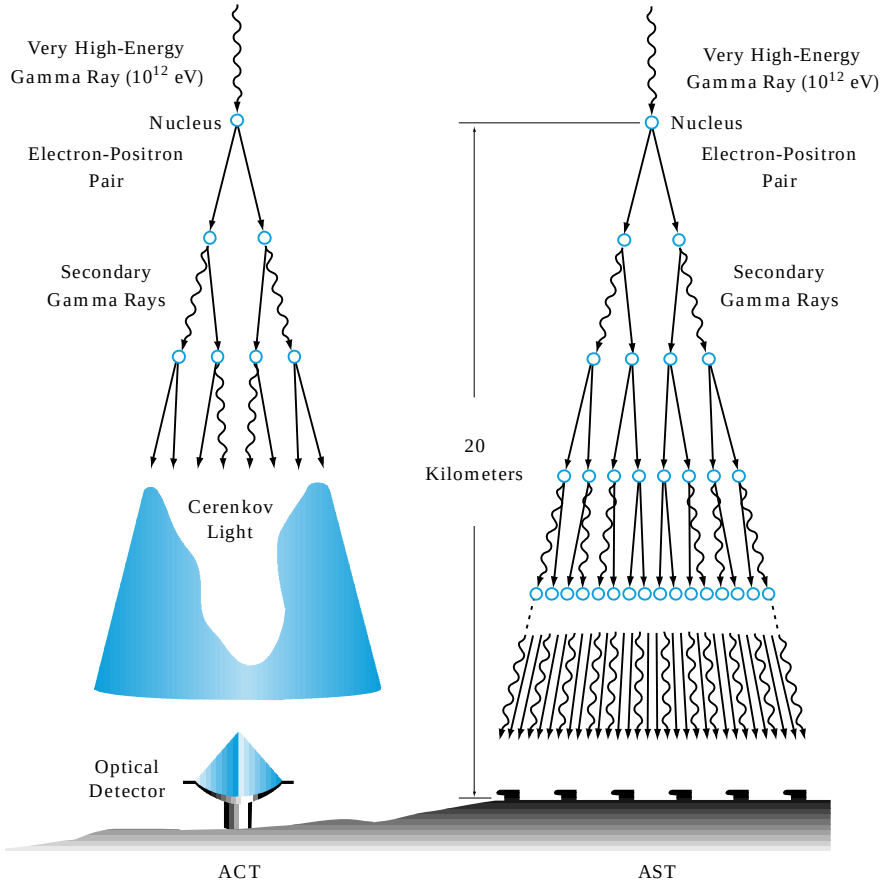
0.01 steradians, corresponds to a relativistic mass conversion rate of more than one millionth of a solar mass per year! It is extremely efficient in generating nonthermal gamma radiation. Trevor Weekes of the Whipple Observatory in Arizona has described these observations as if "we are looking down the barrel of a gun, or a powerful cosmic jet, to see how it works."

NATURE'S GIFT

What makes it possible to detect such small fluxes? Most space-based instruments are limited in size, having a collecting area of only few square meters, and hence they become insensitive to detection at energies above about 10 GeV, because the flux decreases so rapidly with energy. Instead, we have to rely on the atmosphere to spread out the influence of each individual gamma ray over a large area. The very high-energy gamma rays, coming from a distant source, interact in the upper atmosphere and in so doing generate a large splash or cascade of particles, consisting mainly of electrons and positrons and photons, which all move at or almost at the speed of light. This cascade process serves two purposes: first, it transforms a single high-energy gamma ray into a very large number of fast-moving charged particles; and second, it spreads these particles out over a huge area.

The relativistic particles generate a flash of Cerenkov light, an electromagnetic shock wave which air Cerenkov telescopes (ACT) can detect. Those particles, both charged and neutral, that manage to penetrate down to ground level can be detected by air shower telescopes (AST). Conversion of a single gamma ray into either a light flash or a particle swarm is shown schematically in the illustration on the left. The effective collecting area for Cerenkov light is greater than 25 acres and for an air shower is greater than 2.5 acres at energies around 1 TeV. Such large areas make it possible to detect the minute fluxes of these high energy gamma rays.

The longitudinal and lateral development of a gamma ray shower in Earth's atmosphere, which spreads the influence of the single incident gamma ray over a large area at the surface of the earth. The left illustration is the spread of the Cerenkov light pool, and at the right is the spread of air shower particles. The Cerenkov light is collected by an optical light collector, and the air shower is sampled by a set of detectors spread out on the ground.

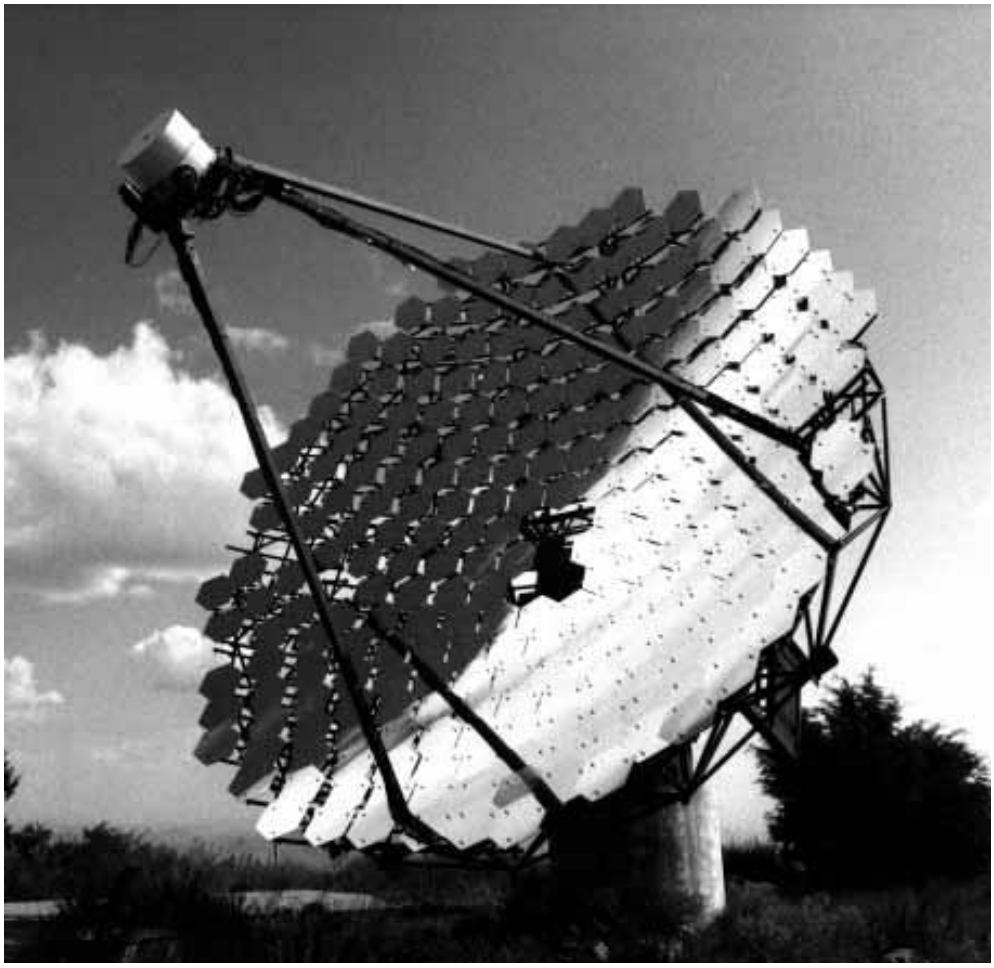


CERENKOV AND AIR SHOWER TELESCOPES

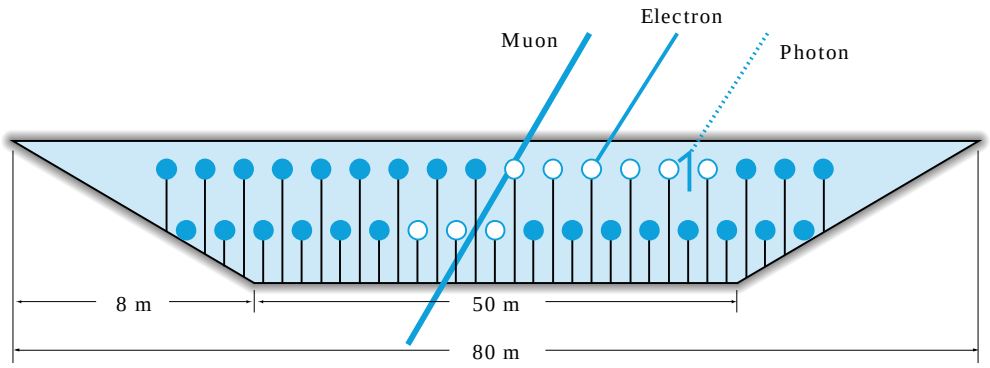
Cerenkov Telescopes. The Cerenkov light pool reflects mainly the longitudinal development of the particle cascade. This light is detected by a Cerenkov telescope, which has a large optical mirror that is typically five or more meters in diameter. The Whipple telescope shown on the right is 10 meters in diameter (33 feet) and produces an image of the cascade in a high speed camera. The camera needs to be very fast because the Cerenkov flashes last only a few nanoseconds. These telescopes, like other optical instruments, are currently restricted to operating on dark nights and can point only at one source at a time. Typical observation times are a few hours each night.

Cerenkov imaging telescopes have a powerful capability: they can discriminate against events generated by ordinary cosmic rays. Showers are produced not only by the gamma rays we desire to see but also by the much more copious cosmic rays. It is therefore imperative to discriminate against these cosmic ray background showers. This is done in imaging Cerenkov telescopes by requiring that the shape of the image correspond to a gamma-initiated shower and not to a cosmic ray shower. This was first achieved by the Whipple collaboration at Mt. Hopkins in Arizona. They are able to reject over 95 percent of cosmic ray showers. One other advantage of the Cerenkov technique is that it can measure the total light generated by the shower, which is proportional to the energy of the primary gamma ray. Finally, the ACT technique has superior angular resolution, which also makes it possible not only to reject cosmic rays but also to study the spatial properties of sources that are not point-like. The Whipple telescope has established the Crab Nebula as a standard candle and has been the first to detect the two extragalactic sources, the Blazars Mrk 421 and Mrk 501, mentioned previously.

The limitations of imaging Cerenkov telescopes are that it is difficult for them to observe more than one source at a time, and they are not operative all the time as they require dark nights. These difficulties are being overcome through the use of a new AST technique that is ideally suited for continuous operation, day



The Whipple Observatory 10 m optical collector and its imaging camera on Mt. Hopkins in Arizona. The imaging camera consists of a cluster of photomultipliers that make a fine-grained image of the sharp Cerenkov light pulse. (Courtesy Whipple Observatory)



Schematic cross section of the Milagro detector showing the two layers of photomultipliers (circles). The lighter circles represent tubes that have responded to the Cerenkov light emitted by air shower particles traveling through water. Three different kinds of air shower particles are indicated: electrons (positrons); MeV gamma ray photons; and penetrating muons. The signals from all responding PMTs are recorded—both time of hit and size of the pulse—from which the arrival direction can be reconstructed.

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

Whipple Telescope
http://egret.sao.arizona.edu/links.html

MAGIC
http://hegra1.mppmu.mpg.de:8000/MAGIC/

Milagro
http://umdgrb.umd.edu/~milagro/project_summary

Veritas
http://pursn3.physics.purdue.edu/veritas/

STACEE
http://hep.uchicago.edu/~stacee/

or night, and that can monitor the overhead sky.

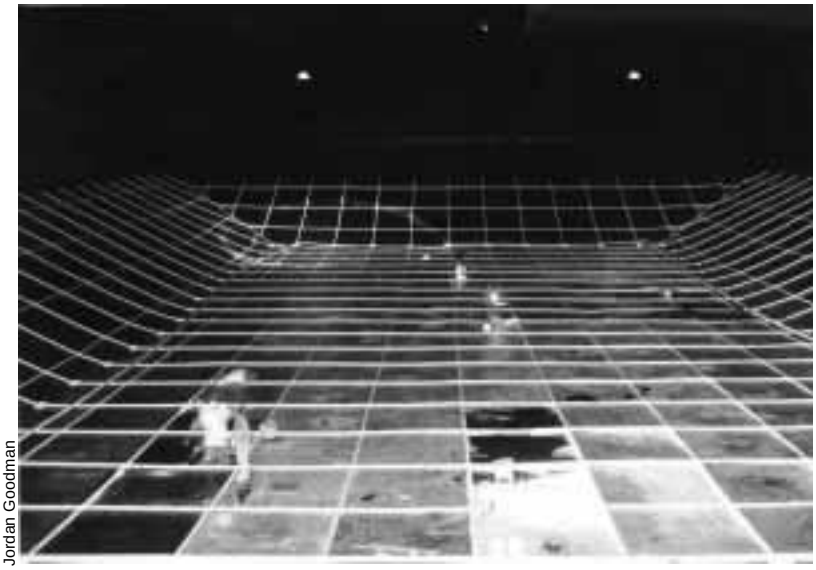
Air shower telescopes. Conventional ground-based air shower telescopes consist of a collection of detectors, such as scintillation counters which respond to the passage of charged particles spread out over more than 2.5 acres. These counters typically provide an active area coverage of only about one percent. To be able to detect showers produced by TeV primaries, it is imperative to build arrays at high altitudes as the maximum number of shower particles occurs high up in the atmosphere. One small array has been operating at Mt. Chacaltaya, Bolivia, at 17,000 feet for many years, first started in the 1960s by George Clark of the Massachusetts Institute of Technology.

A modern shower array dedicated to searching the skies for very high-energy gamma rays is the Tibet Array, operating at about 14,000 feet at Yanbajing, a few hours from Lhasa. This array is shown on pages 12 and 13. It has a threshold energy of a few TeV. Particle showers from the air shower hitting the array are detected. These particles form a swarm that is a few nano-lightseconds in thickness. Hence by measuring the arrival time and pulse heights of the responding detectors one can reconstruct the content of the shower as well as its direction to an accuracy of about a half of a degree.

A new type of air shower telescope, called Milagro (or "miracle" in Spanish), is under construction at about 9000 feet in the Jemez mountains in New Mexico. It consists of a large pond (80m × 60m × 8m deep) of water that is instrumented with 840, 8-inch photomultipliers (PMTs). As the showers produced by the desired gamma rays as well as cosmic rays hit the pond, they contain electrons, positrons, MeV gamma rays, muons, and hadrons. Upon entering the water, all of these particles produce Cerenkov light, which is then detected by the photomultipliers. The pond is encased in a light-tight bubble (somewhat like a tennis court bubble but black), so that the pond is sensitive day and night. It is fully sensitive over its entire area of 5000 m^2 or the size of a typical football field. A schematic of the cross section of Milagro is shown in the illustration above left. The pulse height and time signals from these PMTs are recorded, and the event is reconstructed online to yield information about the energy of the shower and the direction of the originating particle.

The performance of this instrument has been tested in its first phase, called Milagrito. It has been operated for about a year and a half. The photographs on the next page illustrate some of the features of this novel telescope.

The advantages of the Milagro telescope are that it is operational day and night; it views the entire overhead sky all the time; and it is particularly suited to observation of transients. When in full operation it will be sensitive down to a few hundred GeV, thus overlapping the



Jordan Goodman

Above left. The Milagro pond is enclosed in a light-tight inflated cover that can withstand the weather. It is possible to work under the cover for installation or maintenance activities.
Above right: A view of the Milagro volume under the cover. The structure is used to anchor the photomultipliers on a 3m× 3m grid. The photomultipliers are attached to the grid by strings and rise to their required position by buoyancy force.

energy range of ACTs. With the addition of an array of water tanks outside the pond, Milagro will have sensitivity into the high energy range of 10 to 100 TeV as well. At these higher energies Milagro will have the unique capability of detecting the muons that are produced only in cosmic ray showers. This will provide for cosmic ray rejection at higher energies and a means of extending the energy spectrum into the region where a cutoff is expected to the absorption of gamma rays in transit from source to Earth by ambient background photons.

WHERE ARE WE GOING WITH VHE ASTRONOMY?

The air Cerenkov and air shower telescopes described here are not the only ones that are currently being constructed or proposed. These instruments are intended to explore what we have currently defined as the very high-energy gamma ray region. There remains an energy gap, between 10 GeV and a few hundred GeV, that is still virgin territory. Satellite or space station-based instruments, such as GLAST and AMS, are currently under development; these will correspond to second generation versions of the Compton Gamma Ray Observatory and should explore the 10 to 100 GeV sky. Certain ground based instruments are also being constructed to span this energy gap. One example, called STACEE, is being constructed in New Mexico using solar collectors at Sandia Laboratories. A new proposal from Germany, called MAGIC, would build a 17 m optical collector to image the Cerenkov light from showers in this energy range with an advanced camera. A multiple imaging Cerenkov telescope is being constructed on Mount Abu in India. A multiple mirror array of telescopes of the Whipple design, called Veritas, is being vigorously pursued in the U.S. under the leadership of the Whipple collaboration. A comparison of light flux sensitivity, collection areas, and energy thresholds for ACT telescopes coming into operation or whose proposals are actively being pursued is given in the table below. These instruments will increase the sensitivity for source searches by over two orders of magnitude and lower the energy threshold by a factor of about ten compared to those of currently operating ACT telescopes. This partial list of projects indicates that in the next decade we should have gamma ray coverage of the high-energy universe from a few hundred MeV to 100 TeV. We can look forward to providing much-needed clues to understanding non-thermal energetic processes in the Universe, and perhaps even the question of the origin of cosmic rays.

Light flux sensitivity, collection areas, and energy thresholds for some contemporary telescopes.

Telescope	Minimal Photon Flux (photons/m^2)	Collector Area (m^2)	Energy Threshold (GeV)
Whipple 98[a]	16	74	100
Veritas[b]	10/telescope	9×74	60
MAGIC[c]	1–2	234	20
STACEE[c]	2–5	Large	30–80

[a]The upgraded Whipple telescope will be operating in 1998.
[b]Projects in proposal stage.
[c]Currently under construction.

Citius, Altius, Fortius: Astrophysical Sources Above 10^1

THIS WAS THE YEAR when you finally had to take your other hand out of your pocket to count the TeV sources whose detection most of us would bet a few pennies on. (If you find an astronomer who can afford to bet more than a few pennies on this sort of thing, he probably has his hand in somebody else's pocket.). The shoes should be able to stay on for at least a few more years, until the Mega-machines described elsewhere in this issue have piled up a few mountains of data.

There are, in fact, fewer sources around now than there were a decade or so ago. Up to 1991, TeV and even PeV emission had been reported for the X-ray binaries Cygnus X-3, Hercules X-1, Vela X-2, LMC X-1, 4U 0115+53, 4U 1822-37, and Scorpius X-1 and the pulsars 0532 (in the Crab Nebula) and 1509-58 (in the supernova remnant MSH 15-52). In case you wondered, "4U" means something in the Fourth Uhuru (X-ray) Catalog, and MSH is the radio astronomers Mills, Slee, Hill (rapid repetition of which counts as a sobriety test). These X-ray binaries are a fine mix of ones with high and low mass companions and with neutron star and (probably) black hole primaries. Most of the reports included evidence for variability at a rotation or orbit period (desired because positional accuracy was very poor). Truly spectacular was Cyg X-3, whose high energy emission seemed to act more like hadrons than photons, leading to the invention of cygnets.

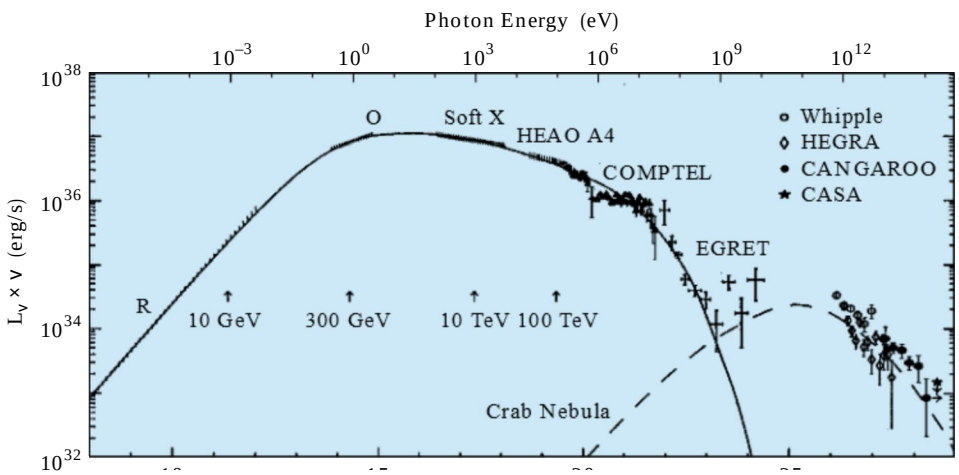
by Virginia Trimble

eV Per Something

Most of these sources have not been seen convincingly for a decade or more, despite (or perhaps because of) the commissioning of more sensitive detectors with sharper angular resolution. Cyg X-3 and Her X-1, especially, must have a very small ratio of "on time" to "off time." Zero is not excluded. The critical period was 1989–1991, when the Whipple Cerenkov telescope in Arizona and the Cygnus air shower array in New Mexico started scanning the TeV and PeV skies respectively, and setting a lot of upper limits.

SUPERNOVA REMNANTS

Whipple did, however, see the Crab Nebula. Not the pulsar, which phases out in the MeV to GeV range probed by the Compton Gamma Ray Observatory (as do the other six known gamma-ray pulsars), but steady emission from some part of the nebula. This emission is probably even understood as inverse Compton scattering of synchrotron photons at lower energies by the relativistic electrons that have to be there anyhow to radiate the synchrotron (this is a little like having your hand in your own pocket and pretending not to notice). The source is, therefore, indirectly the pulsar, which is responsible for accelerating said electrons, but more directly a pulsar-driven wind and nebula, as modeled back in 1984 by Charles Kennel and Ferd Coroniti.*



Observed and modeled spectrum of the Crab Nebula from radio to TeV energies. Numbers under the arrows are the energies of electrons that must be present to radiate those frequencies in the known magnetic field of the nebula (Courtesy Felix Aharonian)

**The basic equations are all in a 1965 paper by Bob Gould, but not much was known about pulsars in those days. Though Richard Haymes' balloon group had already seen the Crab pulsar as a gamma ray source, they didn't know it yet.*

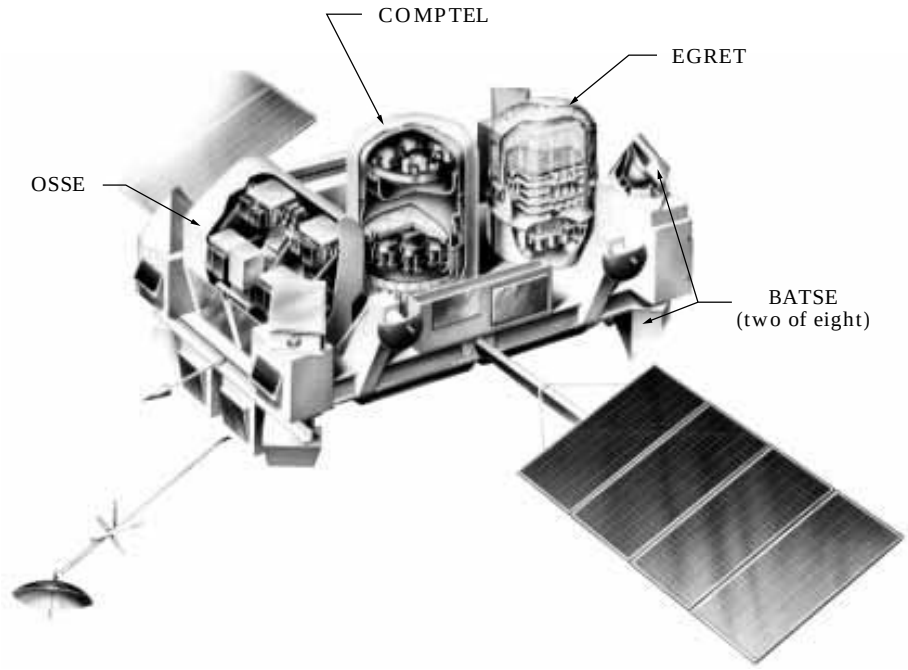
The same is true for the second pulsar-related source, found by the CANGAROO collaboration in the vicinity of PSR B1706-44. The pulsar is about 1.8 kpc away, about 17,500 years old, and near the center of the supernova remnant G343.1-2.3. ("G" means the position is given in galactic coordinates, and cognoscenti can figure out that either position means only southern observers can study the thing.) The radio period is 0.102 sec, but the high energy gamma rays are largely unpulsed, and no optical counterpart has been identified so far. Unpulsed emission from the vicinity of the Vela pulsar may be a third, similar case.

Shell-type supernova remnants, with no evidence for central pulsars or neutron stars, are frequently also synchrotron sources, opening up the possibility for inverse Compton gamma rays from them as well. The brightest supernova of historic times, SN 1006, left such a remnant, whose gamma rays, up to 100 TeV, have recently turned up in the CANGAROO data, along with upper limits for a number of other supernova remnants and pulsars. It is another southern source, and the supernova barely peeked above the horizon in China and Switzerland where it was discovered.

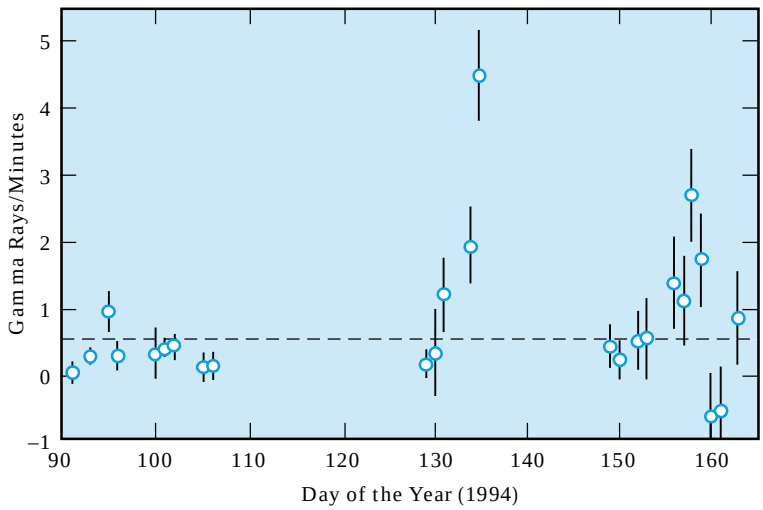
BLAZARS

Blazars are a subset of active galaxies, along with radio galaxies and quasars, quasi-stellar objects (not radio sources), several types of Seyfert galaxies, and so forth. The term is a sort of portmanteau, incorporating both the idea of blazing and the name of the prototype object, BL Lacertae (meaning that it was once thought to be a variable star in our own galaxy). Blazars are the ones with not much stray gas around to get in the way of narrow, beamed cones of relativistic stuff, that are somehow collimated by a magnetized accretion disk around a supermassive black hole, and aimed by chance more-or-less straight at us. Signatures include weakness or absence of emission lines, rapid variability in flux and in polarization of visible light, X-ray emission, and compact radio emission with a flat spectrum and a core-jet structure that changes fast enough to be called "superluminal motion" (meaning that if you forget to include special relativity correctly in your calculation, you will end up thinking that the source violates the $v \leq c$ speed limit).

The Compton Gamma Ray Observatory, an enormously productive mission, still yielding valuable information about stellar, galactic, and other sources of radiation at energies lower than the ones addressed in this set of articles.



The 1994 flare of blazar Mrk 421 as seen by the Whipple Observatory. An X-ray high state occurred twenty-seven hours later. (Courtesy Whipple Observatory)



The first eighteen months of discoveries from the Compton Gamma Ray Observatory included probable EGRET detections of about fourteen blazars at $E \geq 100$ MeV, and the number has increased to fifty or more (though a few are probably chance coincidences). Most are variable, and some are quite distant. Theorists immediately beefed up their beams to make gamma rays as well as X rays. This tended to mean that both the largest energies of individual particles in the beam and its bulk velocity had to get bigger.

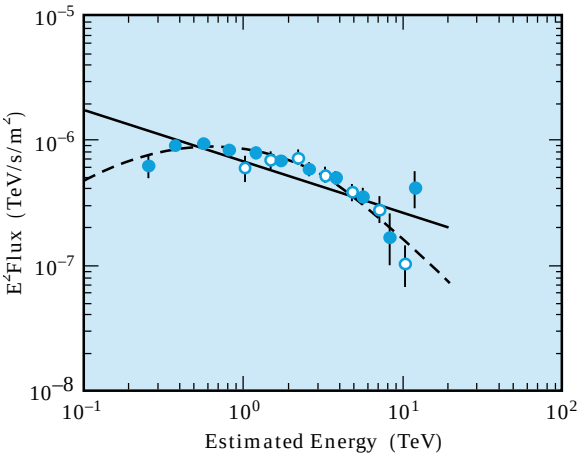
What is the beam made of? One school of theorists favors electrons that Compton up-scatter X-rays and other lower-energy photons, as in the gamma-ray supernova remnants. The alternative is a mostly hadronic beam, with the gamma rays coming from secondary pion production. In fact, relativistic tomatoes will work about as well as anything else, if you can figure out how to accelerate them (a point noted many years ago by Franco Pacini). If the bulk motion has $\gamma = (1 - v^2/c^2)^{-1/2} = 10$ or more (needed anyhow for the superluminal motions and so forth) then the maximum energy of photons coming out depends primarily on the energies of the individual particles in the beam.

The theorists were still hard at work shocking the beams and each other to reach beyond 100 MeV when Markarian (Mrk) 421 was recorded as a TeV source at the Whipple Observatory in 1991. Confirmation by the HEGRA installation in the Canary Islands followed in due course. Mrk 421, at $z = 0.0308$, is the closest of all the superluminal sources. As a result, not only is $1/r^2$ in our favor, but the probability of photons being wiped out by gamma-gamma interactions and pair production en route to us is much reduced. The TeV gamma rays flared spectacularly a couple of years after their discovery, but the source is detectable the rest of the time at a flux level about one--quarter that of the Crab Nebula. Apparent correlations of TeV and X-ray flares slightly favor the Compton up-scattering models.

Next came Mrk 501, just a little further away and just a little fainter, again seen first at the Whipple Observatory and then at HEGRA (just before the summer 1997 fire there knocked it out).

At this point, one knew one needed theorists for two things: since there are closer, non-blazar active galactic nuclei (AGN) not detected, somebody has to work on the details of the beam; and since there are slightly more distant, but brighter, blazars also not detected, somebody has to work on the details of how far TeV gamma rays can travel though the photon sea of intergalactic space.

This second point wouldn't be very interesting except that the cross section for pair production is largest when $E(\gamma_1) \times E(\gamma_2) \approx 2\,(m_e c^2)^2$. In other words, photons with wavelengths of 20–50 μm are the most damaging, and we know practically nothing about the intergalactic background in that band.



The slightly sagging TeV spectrum of Mkn 501. The upper power law is what should be radiated by inverse Compton scattering (given the electron and photon energies one knows from the optical emission). The lower one is what we see, and the sources should disappear completely both at slightly higher energies and at slightly larger distances. (Courtesy Whipple Gamma Ray Collaboration)

Approaching the problem from the other, observational, side, we can say that both Mrk 421 and Mrk 501 have spectra that are beginning to droop below a power law at 10 TeV, which could be a signature of incipient pair production (or, of course, of a droopy beam). Helpfully, the third Whipplet which rejoices in the name 1ES 2344+514 and was published in summer 1998, has a slightly larger redshift of 0.044 and a spectrum that may not continue above about 1 TeV. It has been seen only when flaring.

When upcoming projects push Cerenkov techniques to slightly lower energies, we ought to be able to map out the mid-infrared background using the sagging sub-TeV spectra of additional blazars, and perhaps even verify that the background is the same in different directions. Yuri Neshpov and his Crimean colleagues have also reported TeV emission from the radio source 3C 66A. It is not an EGRET source, but then neither are Mrk 501 and 1ES 2344+514, while Mrk 421 is, so there are real differences in intrinsic spectra as well as in propagation effects.

GAMMA-RAY BURSTERS

The optical identification of several of these with entities at redshifts $\gtrsim 1$ means that photons of TeV and higher energies will have a very difficult time getting to us, though they might well be produced at otherwise detectable fluxes. The same applies to very high-energy protons that might otherwise contribute to the cosmic ray background. But neutrinos of 10^{14} eV and more should be co-produced and are unlikely to be scattered or degraded along the way.

COSMIC RAYS

We come at last to a territory where the papers do not outnumber the detections. A 10^{12} eV or even a 10^{15} eV cosmic ray is hardly worth mentioning, they are so common. At some point, though, we should stop calling them "galactic cosmic rays," on the grounds that they can leak both in and out of the galactic micro-Gauss magnetic field, and so need not have been accelerated here or have a higher energy density inside galaxies than outside.

TeV and PeV cosmic rays don't even present any particular theoretical problem, in the sense that they are seen to be a mix of protons and heavier nuclei (the mix varying somewhat with energy) and that they can be accelerated in shocks and magnetic fields around supernovae, neutron stars, AGNs and so forth. They come to us isotropically and cannot be associated with any particular sources. Individual supernovae may, however, contribute a large fraction of the flux at particular times. The evidence for this is apparent changes in the average local GCR density as measured from cosmic-ray tracks in meteorites.

The first three cosmic ray events above 10^{20} eV (one each from the Yakutsk, Fly's Eye, and AGASA experiments) were consistent with an isotropic distribution, and none seemed to be coming from the direction of any interesting source, like a nearby Seyfert or radio galaxy.

With increasing numbers, more elaborate statistical analysis has become possible. This has naturally resulted in some authorities concluding that the arrival directions are paired or clustered or associated with the supergalactic plane, and others concluding that the arrival directions are random. Larger numbers of events will inevitably resolve the issue (though students of gamma ray bursters were still having a very similar argument when the number approached 2000).

The difficulties start as soon as you ask what the primary particles are. If this is phrased as, "Are they mostly protons or heavier nuclei?" then even the answer "yes" would be helpful.* The troubles with either of these candidates are that (a) they are not very easy to accelerate to 10^{20} eV (and tomatoes are no easier), and (b) they cannot travel more than about 100 Megaparsecs through the intergalactic photon bath. The main enemy is the cosmic microwave background, because that is where most of the photons are. At least we know how many with some precision, so the calculation is a straightforward one. A distance of 100 Mpc corresponds to a redshift of only 0.017 to 0.033, and barely carries us to the nearest blazar (which is not, anyhow, in any of the arrival directions).

Readers may recall other questions where something similar applies, for instance "Is it a boy or a girl?" when asked about an infant member of the Addams family, and "Is the Universe open or closed?" as a test of whether the standard, hot big bang covers all the likely alternatives.

One theoretical camp nevertheless remains reasonably comfortable with a scenario in which protons are pushed to 10^{20} eV in the relativistic jets of radio sources, meaning the ones associated with massive black holes in galactic centers, but perhaps also the ones associated with stellar-mass black holes in the two known "mini-quasars" or superluminal sources in the Milky Way (though again neither of these is in a useful direction).

The other camp has put forward more exotic scenarios, in which, for instance, topological defects like monopoles and cosmic strings, left from phase transitions in the very early, hot universe, decay to some sort of supermassive X-particles, which then decay to ordinary baryons at very high energies. Because the decays are not strongly confined to galaxies, their products can come to us from any direction, and need not have traveled very far. The processes must not, of course, be allowed to mess up anything else we see, like the products of big bang nucleosynthesis or the diffuse gamma-ray background. This probably rules out superconducting strings as the initial defect. On the other hand, you can use the same X-particle to account for the baryon excess of the Universe. A slight variant invokes decaying dark matter particles that are specifically confined to the extended halo of the Milky Way and which therefore yield high energy particles that seem roughly isotropic and have hardly any distance to travel.

CONCLUSION

The highest energies you can think of, for photons, neutrinos, and other particles, are one of the windows to the Universe that is still fairly opaque. Opening it will undoubtedly reveal some unfamiliar scenery. The same can be said for the lowest radio frequencies (less than a few MHz), the vacuum ultraviolet (where there has never been an all-sky survey), and the band around 10 GeV, where photons are too few to be caught in space and too feeble to be seen from the ground.

HONEY, I SHRUNK THE SUN

Even before I had seen the summer 1998 issue of *Beam Line*, readers were emailing to point out that the correct ratio of the mass of the Sun to that of Earth is about 300,000, not 300. This is unquestionably true! I had simply copied Newton's and Encke's and modern numbers from a table in a standard history of solar physics, where the author did not emphasize that he was tabulating "milli-somethings." My apologies to Newton, anyone who strained his back trying to lift the sun as a result of the misinformation, and all others concerned.

TESLA
The Superconducting Linear

by REINHARD BRINKMANN

Superconducting niobium cavities offer an alternative path to a TeV linear collider. Extensive R&D on this approach has stimulated the conceptual design of such a machine.

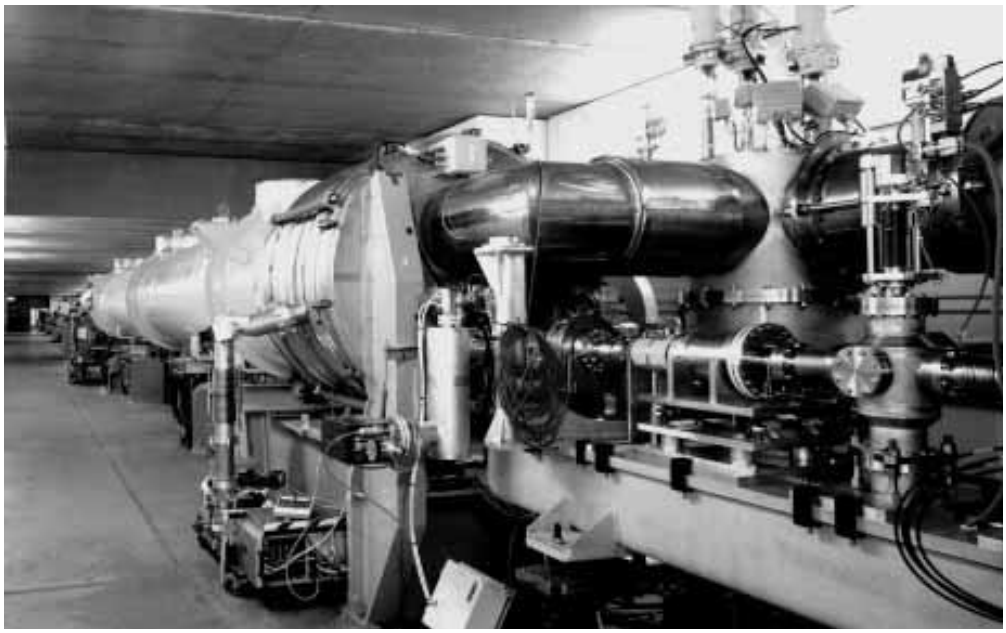
SEVERAL FUNDAMENTAL PROBLEMS of particle physics concerning the high-energy behavior of matter are expected to be solved—at least in principle—by studying collisions of particles at energies almost an order of magnitude higher than those reached by accelerators operating today. The next step in this direction will be the Large Hadron Collider, a proton-proton storage-ring collider being built as an international effort at the European laboratory CERN in Geneva. But there now is widespread agreement that this machine should be complemented by other colliders in which leptons—in particular electrons and positrons, but eventually perhaps muons—annihilate, allowing a cleaner study of the reaction products.

To reach the required energies with electrons and positrons, a pair of linear accelerators firing at one another seems to be the most feasible technical solution. Storage rings for such light particles are limited in energy because of their energy losses due to synchrotron radiation. Studies of various linear-collider designs are being pursued at several laboratories as described by Gregory Loew and Michael Riordan in the Winter 1997 *Beam Line*, Vol. 27, No. 4. One of these approaches is the TESLA concept, or "TeV-Energy Superconducting Linear Accelerator," which should initially reach a collision energy of at least 500 GeV. The TESLA project is being pursued by a broad international collaboration coordinated at DESY in Hamburg; more than thirty

Collider

institutions from China, Finland, France, Germany, Italy, Poland, Russia, and the United States are participating in it.

THE TESLA CONCEPT is based on superconducting cavities made of niobium metal and operating at superfluid helium temperature (2K). The energy losses in the walls of such superconducting microwave cavities are extremely low, leading to a ratio of the stored power to the power lost by damping, the so called "quality factor," of the order of 10^{10}—a *million* times higher than in a normally conducting, room-temperature copper cavity. This allows one to operate a superconducting linear accelerator at a relatively low frequency (1.3 GHz for TESLA) and with long pulses that can be generated by a low-peak-power microwave source. A high efficiency of power transfer to the beam is possible. And, at the lower frequency, the wakefields induced by the beam in the surrounding structures are small while the required alignment tolerances are quite moderate (0.5 mm for the cavities). All this makes a superconducting linac



TESLA nine-cell niobium cavity ready for installation in the vertical test cryostat for performance testing. (Courtesy DESY)

Assembly of the first string of eight TESLA cavities in the clean room at the Test Facility. (Courtesy DESY)

ideal for accelerating a beam of extremely good quality—with small transverse dimensions and angular divergence ("low emittance") and with a low energy spread, that is exactly what is required for a high-performance linear collider. Consequently, there is in principle also a strong potential for TESLA to achieve high collision rates, corresponding to a luminosity of as much as $3–5\times10^{34}$ $cm^{-2}s^{-1}$, as compared with 3×10^{30} achieved so far on the Stanford Linear Collider at 50 GeV beam energy and about 5×10^{31} on the LEP collider at CERN at 90 GeV. This potential high performance of TESLA coincides with a low background environment and good energy resolution for particle-physics experiments.

But there is also a major challenge: superconducting accelerator systems are known to be expensive. The TESLA collaboration has set an ambitious goal for reducing the cost per megavolt (MV) of accelerating voltage by a factor of 20 compared to what has so far been realized at existing large-scale installations (such as Jefferson Lab and in the superconducting cavities of the LEP ring). The goal is $2000 per megavolt, to be achieved by increasing the accelerating gradient fivefold in comparison with the 5–6 MV/m typical of existing facilities, and by reducing the cost per unit length by a factor of four. In order to demonstrate that this goal can be reached, an aggressive R&D program was launched in 1992.

The TESLA Test Facility, or TTF, has been set up at DESY to serve as a focus for R&D on high-performance superconducting cavities. It includes a fully operational linac in order to perform an integrated system test of all components as they would be used in a future collider. Developments at the TTF will also provide a basis for a complete cost estimate for a 500 GeV machine.

In the test facility the complete infrastructure for processing nine-cell niobium cavities (see top left photograph), as they are obtained from industrial production, is already available. Steps toward achieving high-performance cavities include the required chemical treatment, high-pressure rinsing with ultrapure water and heat treatment up to 1400°C. Each cavity undergoes performance tests with continuous-wave as well as pulsed-mode microwave excitations. Strings of eight cavities are assembled under clean-room conditions (bottom photograph) and mounted into cryogenic modules. In May 1997 the first module of this type was completed and installed in the test linac (photograph on previous page). Within a few days of commissioning of the accelerator, an average accelerating gradient of 16.5 MV/m was demonstrated with an electron beam passing through the cavities. In addition to this encouraging start, test results for cavities from the continuing industrial production show a further performance improvement. The best performance to date was obtained with a nine-cell cavity in pulsed-mode operation (as required for TESLA), reaching a gradient of 33 MV/m at a quality factor of 4×10^{9}.

Assembly of two more accelerator modules with eight cavities each is in progress, with installation into the linac scheduled for autumn 1998 and February 1999. By that time we expect to accelerate a beam with a

gradient of 25 MV/m. The R&D program towards even higher gradients will continue. The theoretical limit for niobium cavities is about 55 MV/m; single-cell cavities have attained 40 MV/m in tests at Jefferson Lab and KEK. Therefore the TESLA team is confident that operation of a superconducting linac above 30 MV/m will eventually be feasible.

Artist's conception of the main TESLA linac in a 5 meter tunnel.

A COMPLETE DESIGN of the overall layout for TESLA as a next-generation linear collider facility has been developed and documented in an extensive report published in the spring of 1997. The two volumes of this report, titled "Conceptual Design of a 500 GeV e^+e^- Linear Collider with Integrated X-Laser Facility," (available as ECFA-Report 1997-182 and as DESY Report 1997-048), include discussions of the physics involved and the experimental detectors required. In addition to the main linacs, the report details subsystems such as the required particle sources, bunch compressors and damping rings, and the final-focus system needed to compress the beams at the interaction point. An alternative S-band linear collider (considered as a backup solution) is also discussed, as well as a super-brilliant X-ray laser facility.

The site length of 32 km permits a total collision energy of 500 GeV, assuming an accelerating gradient of 22 MV/m. All subsystems of the machine have been designed so that an energy of 800 GeV can be reached with improved cavity performance at a gradient of 34 MV/m. Within the TESLA collaboration there is broad agreement that the site of the next linear collider should be adjacent to an existing high energy physics laboratory; this will provide significant advantages with regard to both the cost and the construction time required for such a facility.

As the coordinating laboratory of the collaboration, DESY has begun to investigate in detail the possibility of constructing TESLA adjacent to its own Hamburg site (which, however, does not rule out other options). The geographical conditions are favorable along a 32 km line stretching northwest from DESY (see illustration on page 25). The machine would sit in a tunnel 15–20 meters underground, very similar to the 6.3 km HERA tunnel. At the electron- positron collision point near Ellerhoop (16 km from DESY) a central site would accommodate the experimental hall for the particle-physics detector and additional infrastructure, as well as the user facility for the X-ray free electron laser.

The proposed TESLA site lies mostly in the "land" of Schleswig-Holstein and in part on territory of the city of Hamburg. The political authorities of both regions and the involved communal administrations have all given their support to the project; they have been very

cooperative in investigating the feasibility of the required construction.

The direction of the linac has been chosen such that it connects tangentially to the HERA ring, thus allowing the possibility of a linac/ring electron-proton collider option at a collision energy 3–4 times the present HERA energy (300 GeV). Furthermore, part of the TESLA linac could serve as an injector for HERA's electron ring, which would be converted into a pulse stretcher to provide a continuous electron beam at 15–25 GeV for nuclear-physics experiments.

The proposed TESLA facility includes a coherent X-ray source in the angstrom wavelength (10^{-8} cm) range; it would serve a broad scientific user community and continue a long DESY tradition of providing experimental facilities for both elementary-particle and synchrotron-radiation research. The X-ray free-electron laser would be able to deliver an extremely high photon flux with a time resolution on the order of 100 femtoseconds and a peak brilliance that exceeds by ten orders of magnitude that of the most advanced synchrotron-radiation sources in existence today.

The first ideas about generating coherent X-rays from a high-energy electron beam using self-amplified spontaneous emission in the framework of a free-electron-laser concept were developed at Stanford University using part of the SLC linac. The TESLA superconducting linac should deliver a particularly good beam quality for this application. The idea is to extract an electron beam from the linac (generated by additional microwave pulses) at various energies (15–50 GeV) and transport it to the central experimental site at which the X-ray user facility is located.

A free-electron-laser test facility using the TTF linac is now under construction at DESY. First tests at a beam energy of about 400 MeV and a wavelength of 40 nanometers will start in the spring of 1999. Further extension to energies over 1 GeV beam energy and 6 nanometers wavelength is planned for subsequent years; operation as a pilot user facility is scheduled to begin in 2001.

IN CONCLUSION, the TESLA collaboration has worked out a complete design for a next-generation electron-positron collider based on superconducting linac technology. Our team is convinced that the excellent performance achievable with this approach justifies the considerable R&D on superconducting cavities. The progress at the TESLA Test Facility justifies our optimism that the necessary cost and performance goals can be reached. Within the next two years a comprehensive technical proposal, including a cost estimate, will be completed. Approval of TESLA as an international project can be envisaged for the year 2002 at the earliest. DESY will be prepared to offer a suitable site for this future facility.

*For readers wishing more information on **TESLA**, the following URL may be helpful:*

http://www-mpy.desy.de/desy-acc.html#LC

Unified Field Theory*

by TIM JOSEPH

In the beginning there was Aristotle,
And objects at rest tended to remain at rest,
And objects in motion tended to come to rest,
And soon everything was at rest,
And God saw that it was boring.

Then God created Newton,
And objects at rest tended to remain at rest,
But objects in motion tended to remain in motion,
And energy was conserved and momentum was conserved and matter
was conserved,
And God saw that it was conservative.

Then God created Einstein,
And everything was relative,
And fast things became short,
And straight things became curved,
And the universe was filled with inertial frames,
And God saw that it was relatively general, but some of it was
especially relative.

Then God created Bohr,
And there was the principle,
And the principle was quantum,
And all things were quantified,
But some things were still relative,
And God saw that it was confusing.

Then God was going to create Furgeson,
And Furgeson would have unified,
And he would have fielded a theory,
And all would have been one,
But it was the seventh day,
And God rested,
And objects at rest tend to remain at rest.

Reprinted by permission from the April 6, 1978, edition of the The New York Times. *At the time the author worked for a nutrition program affiliated with Cornell University and wrote science fiction.*

CONTRIBUTORS

PAUL MANTSCH was educated at Case Institute of Technology and the University of Illinois. He spent two years at DESY in Germany and a year at the Massachusetts Institute of Technology before going to Fermilab in 1973.

At Fermilab his early work was devoted to research at the Tagged Photon Lab and various management positions related to superconducting magnets and cryogenics, including eight years as head of the Technical Support Section. He worked for eleven years on the Superconducting Super Collider (SSC) project at Fermilab, first directing the development of superconducting magnets and later as a subsystem manager for the SDC calorimetry.

While brooding over the death of the SSC, Mantsch came under the spell of Jim Cronin and his irresistible call to understand the really high energy cosmic ray particles with really big calorimeters. He is now the project manager for the Pierre Auger Project.

For the last fifteen years, GAURANG B. YODH has searched for signals of very high energy gamma rays from energetic astrophysical objects using air shower techniques. He was a member of the CYGNUS team that built the first air shower telescope dedicated to 100 TeV gamma ray astronomy at Los Alamos National Laboratory. Following that effort he pushed for the development of a novel gamma ray telescope using the water Cerenkov technique. He was also a leader in the building of the Milagro telescope at Fenton Hill in the Jemez mountains in New Mexico—not what you might expect for somebody who spent almost two decades as an experimental particle physicist at the University of Maryland prior to accepting his present position as Professor of Physics at the University of California, Irvine.

Yodh received his PhD from the University of Chicago and is a Fellow of the American Physical Society and the American Association for the Advancement of Science. He is also an accomplished performer on the Indian sitar and is interested in the creation of celestial music. His current research in celestial gamma rays was partly motivated by his desire to understand the origin of ubiquitous cosmic rays.

There used to be two VIRGINIA TRIMBLES. Now, sadly, there is only one. But the younger one now looks a lot like the older one used to, apart from hair color and tooth alignment (which have yielded to some of the progress of modern technology that we celebrate in this issue). Both were born in Los Angeles, California, attended its public schools, learned to type and sew at an early age, and married research scientists (one chemist and one physicist).

REINHARD BRINKMANN has coordinated the linear collider design studies at DESY in Hamburg, Germany, since 1995. Before coming to DESY in 1984, he studied physics at the University of Muenster and received his PhD in Experimental Physics from the Free University of Berlin.

His research interests include magnet lattice design and beam optics, beam dynamics, and the overall design and optimization of accelerator facilities. He is also interested in bicycle riding and music, especially jazz; he plays piano in a modern swing band.

DATES TO REMEMBER

Jan 5–9, 1999	American Physical Society (APS) meeting of the Division of Particles and Fields (DPF 99), Los Angeles, California (APS Meetings Dept., One Physics Ellipse, College, Park, MD 20740-3844 or dpf99@physics.ucla.edu)
Jan 11–Mar 20	Joint Universities Accelerator School (JUAS 1999), on Physics, Technologies, and Applications of Particle Accelerators, Archamps, France (JUAS Secretariat at Archamps, Centre Universitaire de Formation et de Recherche, F-74166 Archamps, France or bholland@cur-archamps.fr)
Jan12–14	Workshop on Scientific Applications of the Linac Coherent Light Sources (LCLS), Stanford, California (Suzanne Barrett, SSRL, MS 99, Box 4349, Stanford, CA 94309-0210 or barrett@ssrl.slac.stanford.edu)
Jan 17–23	Aspen Workshop on Particle Physics — Advances in Particle Physics: Recent Results and Open Questions, Aspen, Colorado (Vernon Barger, University of Wisconsin, Physics Department, 1150 University Avenue, Madison, WI 53706 or awc99@phenxs.physics.wisc.edu)
Jan 18–29	U.S. Particle Accelerator School (USPAS 1999), Nashville, Tennessee (U.S. Particle Accelerator School, Fermilab, MS 125, Box 500, Batavia, IL 60510-0500 or uspas@fnal.gov)
Jan 24–30	17th International Workshop on Weak Interactions and Neutrinos (WIN 99), Cape Town, South Africa (cad@physci.uct.ac.za)
Mar 1–5	International Workshop on e^+e^- Collisions from Φ to J/Ψ, Novosibirsk, Russia (vepp99@inp.nsk.su)
Mar 8–11	Conference on Higgs and Supersymmetry: Search and Discovery, Gainesville, Florida (Yvonne Dixon, Higgs and SUSY Conference, Physics Department, University of Florida, Gainesville, FL 32611 or ramond@phys.ufl.edu)
Mar 20–26	Centennial Celebration and Meeting of the American Physical Society (Combining Annual APS General Meeting and the Joint Meeting of the APS and the AAPT), Atlanta, Georgia (APS Meetings Department, One Physics Ellipse, College Park, MD 20740-3844 or aps100@aps.org or meetings@aps.org)
Mar 29–Apr 2	IEEE Particle Accelerator Conference (PAC 99), New York, New York (Mary Campbell, Conference Secretary, Brookhaven National Laboratory, Bldg. 911B, Box 5000, Upton, NY 11973-5000 or weng@bnldag.bnl.gov)
Apr 6–9	ICFA 17th Advanced Beam Dynamics Workshop on Future Light Sources, Argonne, Illinois (flsworkshop@aps.anl.gov)

May 17–20	Workshop on Polarized Protons at High Energies – Accelerator Challenges and Physics Opportunities, Hamburg, Germany (HERASPIN, DESY, Notkestrasse 85, D-22607, Hamburg, Germany, or heraspin@desy.de)
May 17–20	Workshop on Heavy Ion Theory (HIT 99), Geneva, Switzerland (hit99@surya11.cern.ch)
May 17–20	XIth International Conference on Small-Angle Scattering, Upton, New York (Ann Emrick, Conference Coordinator, emrick@bnl.gov)
May 24–26	NSLS Annual Users' Meetings and Workshops, Upton, New York (Linda Feirabrand, Conference Coordinator, NSLS, lsusrmtg@bnl.gov)
May 26–29	The David N. Schramm Memorial Symposium: Inner Space/Outer Space II, Batavia, Illinois (sazama@fnal.gov)
May 28–Jun 3	CERN Accelerator School Course on Vacuum Technology for Particle Accelerators, Copenhagen, Denmark (CERN Accelerator School, AC Division, CH-1211 Geneva 23, Switzerland or suzanne.von.wartburg@cern.ch)
Jun 7–18	Workshop on Physics at TeV Colliders, Les Houches, France (aurenche@lapp.in2p3.fr or belanger@lapp.in2p3.fr)
Jun 7–Jul 9	ICTP Summer School in Particle Physics, Trieste Italy (ICTP, Box 586, Strada Costiera 11, I-34100, Trieste, Italy (smr1141@ictp.trieste.it)
Jun 14–19	7th International Conference on Supersymmetries in Physics (SUSY 99), Batavia, Illinois (Cynthia Sazama, MS 122, Fermilab, Box 500, Batavia, IL 60510 or sazama@fnal.gov)
Jun 27–30	12th IEEE International Pulsed Power Conference, Monterey, California (Teresa Montero ppc99@llnl.gov)
Aug 9–14	19th International Symposium on Lepton and Photon Interactions at High Energies (by invitation only, Maura Chatwell, SLAC, MS 96, Box 4349, Stanford, CA 94309-4349 or lp99@slac.stanford.edu)