

Cosmic Rays at the Energy Frontier

These particles carry more energy than any others in the universe. Their origin is unknown but may be relatively nearby

by James W. Cronin, Thomas K. Gaisser and Simon P. Swordy

Roughly once a second, a subatomic particle enters the earth's atmosphere carrying as much energy as a well-thrown rock. Somewhere in the universe, that fact implies, there are forces that can impart to a single proton 100 million times the energy achievable by the most powerful earthbound accelerators. Where and how?

Those questions have occupied physicists since cosmic rays were first discovered in 1912 (although the entities in question are now known to be particles, the name "ray" persists). The interstellar medium contains atomic nuclei of every element in the periodic table, all moving under the influence of electrical and magnetic fields. Without the screening effect of the earth's atmosphere, cosmic rays would pose a significant health threat; indeed, people living in mountainous regions or making frequent airplane trips pick up a measurable extra radiation dose.

Perhaps the most remarkable feature of this radiation is that investigators have not yet found a natural end to the cosmic-ray spectrum. Most well-known sources of charged particles—such as the sun, with its solar wind—have a characteristic energy limit; they simply do not produce particles with energies above this limit. In contrast, cosmic rays appear, albeit in decreasing numbers, at energies as high as astrophysicists can measure. The data run out at levels around 300 billion times the rest-mass energy of a proton because there is at present no detector large enough to sample the very low number of incoming particles predicted.

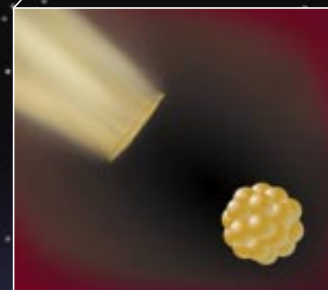
Nevertheless, evidence of ultrahigh-energy cosmic rays has been seen at intervals of several years as particles hitting the atmosphere create myriad secondary particles (which are easier to detect). On October 15, 1991, for example, a cosmic-ray observatory in the Utah desert registered a show-

er of secondary particles from a 50-joule (3×10^{20} electron volts) cosmic ray. Although the cosmic-ray flux decreases with higher energy, this decline levels off somewhat above about 10^{16} eV, suggesting that the mechanisms responsible for ultrahigh-energy cosmic rays are different from those for rays of more moderate energy.

In 1960 Bernard Peters of the Tata Institute in Bombay suggested that lower-energy cosmic rays are produced predominantly inside our own galaxy, whereas those of higher energy come from more distant sources. One reason to think so is that a cosmic-ray proton carrying more than 10^{19} eV, for example, would not be deflected significantly by any of the magnetic fields typically generated by a galaxy, so it would travel more or less straight. If such particles came from inside our galaxy, we might expect to see different numbers coming from various directions because the galaxy is not arranged symmetrically around us. Instead the distribution is essentially isotropic, as is that of the lower-energy rays, whose directions are scattered.

Supernova Pumps

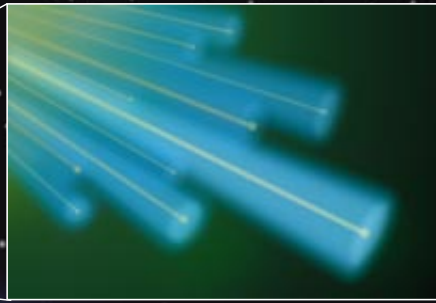
Such tenuous inferences reveal how little is known for certain about the origin of cosmic rays. Astrophysicists have plausible models for how they might be produced but no definitive answers. This state of affairs may be the result of the almost unimaginable difference between conditions on the earth and in the regions where cosmic rays are born. The space between the stars contains only about one atom per cubic centimeter, a far lower density than the best artificial vacuums we can create. Furthermore, these volumes are filled with vast electrical and magnetic fields, intimately connected to a diffuse population of



Cosmic rays—atomic nuclei traveling at nearly the speed of light—inhabit a bizarre relativistically foreshortened universe before smashing into nuclei of atoms of atmospheric gas high above the earth. A significant fraction of the incoming energy is converted to matter in the form of subatomic particles, including muons, which in turn collide violently with other atoms in the atmosphere to create an "air shower." Gamma rays are also emitted.

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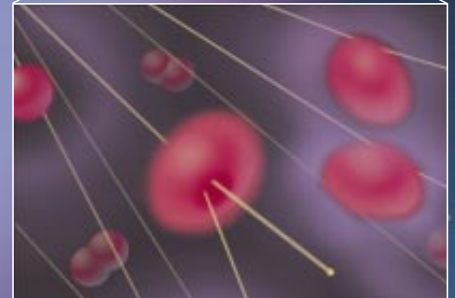
The Life of a Cosmic Ray



Particles in the initial stages of the cascade of collisions are traveling so fast that they exceed the speed of light in the tenuous upper atmosphere (which is negligibly less than the speed of light in a vacuum) and so emit Čerenkov radiation—an optical analogue of a sonic boom.



As the particles created in the initial collision strike atmospheric nuclei, their energy may create additional particles and high-energy radiation. Conservation of momentum dictates that most of the matter created travels in the same direction as the initial cosmic ray, but photons may be emitted essentially in all directions.



Muons and other cosmic-ray debris remaining toward the end of an air shower have dissipated enough energy that their interaction with the atmosphere gives rise mostly to ultraviolet light from the disruption of electron energy shells. This light can be detected by sensitive photomultipliers. In a particularly powerful event, some of the particles from the shower will reach the ground, where they can be detected as well.

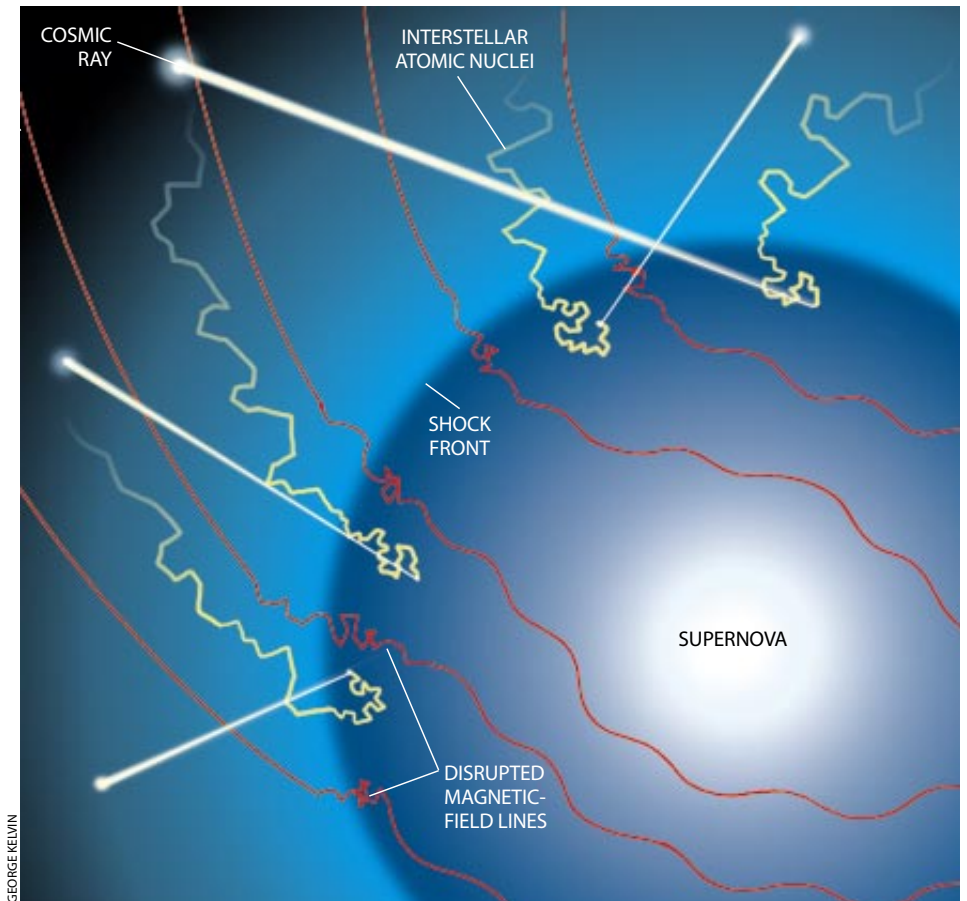
COSMIC-RAY ACCELERATOR is believed to arise from a supernova explosion. Astrophysicists hypothesize that atomic nuclei crossing the supernova shock front will pick up energy from the turbulent magnetic fields embedded in the shock. A particle may be deflected in such a way that it crosses the boundary of the shock hundreds or even thousands of times, picking up more energy on each passage, until it escapes as a cosmic ray. Most of the particles travel on paths that result in relatively small accelerations, accounting for the general shape of the cosmic-ray energy spectrum (*far right*), which falls off at higher energies. The “knee,” or bend, in the curve suggests that most of the particles are accelerated by a mechanism incapable of imparting more than about 10^{15} electron volts. The relative excess of ultrahigh-energy particles indicates an additional source of acceleration whose nature is as yet unknown.

charged particles even less numerous than the neutral atoms.

This environment is far from the peaceful place one might expect: the low densities allow electrical and magnetic forces to operate over large distances and timescales in a manner that would be quickly damped out in material of terrestrial densities. Galactic space is therefore filled with an energetic and turbulent plasma of partially ionized gas in a state of violent activity. The motion is often hard to observe on human timescales because astronomical distances are so large; nevertheless, those same distances allow even moderate forces to achieve impressive results. A particle might zip through a terrestrial accelerator in a few microseconds, but it could spend years or even millennia in the accelerator’s cosmic counterpart. (The timescales are further complicated by the strange, relativity-distorted framework that ultrahigh-energy cosmic rays inhabit. If we could observe such a particle for 10,000 years, that period would correspond to only a single second as far as the particle is concerned.)

Astronomers have long speculated that the bulk of galactic cosmic rays—

AIR-SHOWER DETECTOR watches for traces of cosmic rays entering the upper atmosphere. Photodetectors can track flashes of light caused by particles interacting with air molecules and determine the energy and probable identity of the incoming rays. The Fly’s Eye detector (*close-up at far right*) is located in Utah.

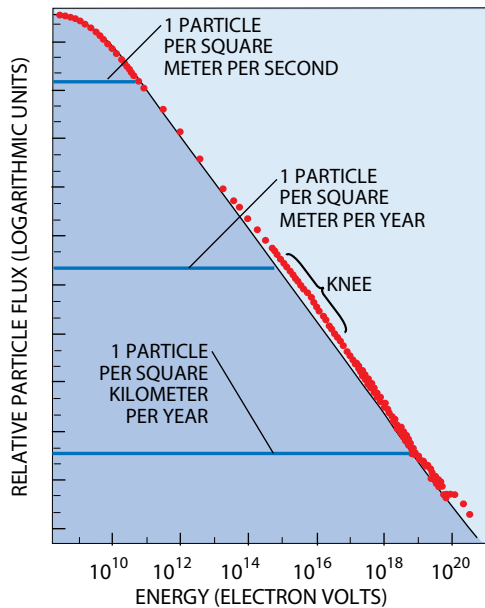


those with energies below about 10^{16} eV—originate with supernovae. A compelling reason for this theory is that the power required to maintain the observed supply of cosmic-ray nuclei in our Milky Way galaxy is only slightly less than the average kinetic energy delivered to the galactic medium by the three supernova

explosions that occur every century. There are few, if any, other sources of this amount of power in our galaxy.

When a massive star collapses, the outer parts of the star explode at speeds of up to 10,000 kilometers per second and more. A similar amount of energy is released when a white dwarf star un-





dergoes complete disintegration in a thermonuclear detonation. In both types of supernovae the ejected matter expands at supersonic velocities, driving a strong shock into the surrounding medium. Such shocks are expected to accelerate nuclei from the material they pass through, turning them into cosmic rays. Because cosmic rays are charged, they follow complicated paths through interstellar magnetic fields. As a result, their directions as observed from the earth yield no information about the location of their original source.

By looking at the synchrotron radiation sometimes associated with supernova remnants, researchers have found more direct evidence that supernovae

can act as accelerators. Synchrotron radiation is characteristic of high-energy electrons moving in an intense magnetic field of the kind that might act as a cosmic-ray accelerator, and the presence of synchrotron x-rays in some supernova remnants suggests particularly high energies. (In earthbound devices, synchrotron emission limits a particle's energy because the emission rate increases as a particle goes faster; at some point, the radiation bleeds energy out of an accelerating particle as fast as it can be pumped in.) Recently the Japanese x-ray satellite *Asca* made images of the shell of Supernova 1006, which exploded 990 years ago. Unlike the radiation from the interior of the remnant, the x-radiation from the shell has the features characteristic of synchrotron radiation. Astrophysicists have deduced that electrons are being accelerated there at up to 10^{14} eV (100 TeV).

The EGRET detector on the *Compton Gamma Ray Observatory* has also been used to study point sources of gamma rays identified with supernova remnants. The observed intensities and spectra (up to a billion electron volts) are consistent with an origin from the decay of particles called neutral pions, which could be produced by cosmic rays from the exploding star's remnants colliding with nearby interstellar gas. Interestingly, however, searches made by the ground-based Whipple Observatory for gamma rays of much higher energies from some of the same remnants have not seen signals at the levels that would be expected if the supernovae were accelerating particles to 10^{14} eV or more.

A complementary method for testing the association of high-energy cosmic rays with supernovae involves the elemental composition of cosmic-ray nuclei. The size of the orbit of a charged particle in a magnetic field is proportional to its total momentum per unit charge, so heavier nuclei have greater total energy for a given orbit size. Any process that limits the particle acceleration on the basis of orbit size (such as an accelerating region of limited extent) will thus lead to an excess of heavier nuclei at high energies.

Eventually we would like to be able to go further and

look for elemental signatures of acceleration in specific types of supernovae. For example, the supernova of a white dwarf detonation would accelerate whatever nuclei populate the local interstellar medium. A supernova that followed the collapse of a massive star, in contrast, would accelerate the surrounding stellar wind, which is characteristic of the outer layers of the progenitor star at earlier stages of its evolution. In some cases, the wind could include an increased fraction of helium, carbon or even heavier nuclei.

The identity of high-energy cosmic rays is all but lost when they interact with atoms in the earth's atmosphere and form a shower of secondary particles. Hence, to be absolutely sure of the nuclear composition, measurements must be made before the cosmic rays reach dense atmosphere. Unfortunately, to collect 100 cosmic rays of energies near 10^{14} eV, a 10-square-meter detector would have to be in orbit for three years. Typical exposures at present are more like the equivalent of one square meter for three days.

Researchers are attacking this problem with some ingenious experiments. For example, the National Aeronautics and Space Administration has developed techniques to loft large payloads (about three tons) with high-altitude balloons for many days. These experiments cost a tiny fraction of what an equivalent satellite detector would. The most successful flights of this type have taken place in Antarctica, where the upper atmosphere winds blow in an almost constant circle around the South Pole.

A payload launched at McMurdo Sound on the coast of Antarctica will travel at a nearly constant radius from the Pole and return eventually to near the launch site. Some balloons have circled the continent for 10 days. One of us (Swordy) is collaborating with Dietrich Müller and Peter Meyer of the University of Chicago on a 10-square-meter detector that could measure heavy cosmic rays of up to 10^{15} eV on such a flight. There are efforts to extend the exposure times to roughly 100 days with similar flights nearer the equator.

Across Intergalactic Space

Studying even higher-energy cosmic rays—those produced by sources as yet unknown—requires large ground-based detectors, which overcome the problem of low flux by watching enor-



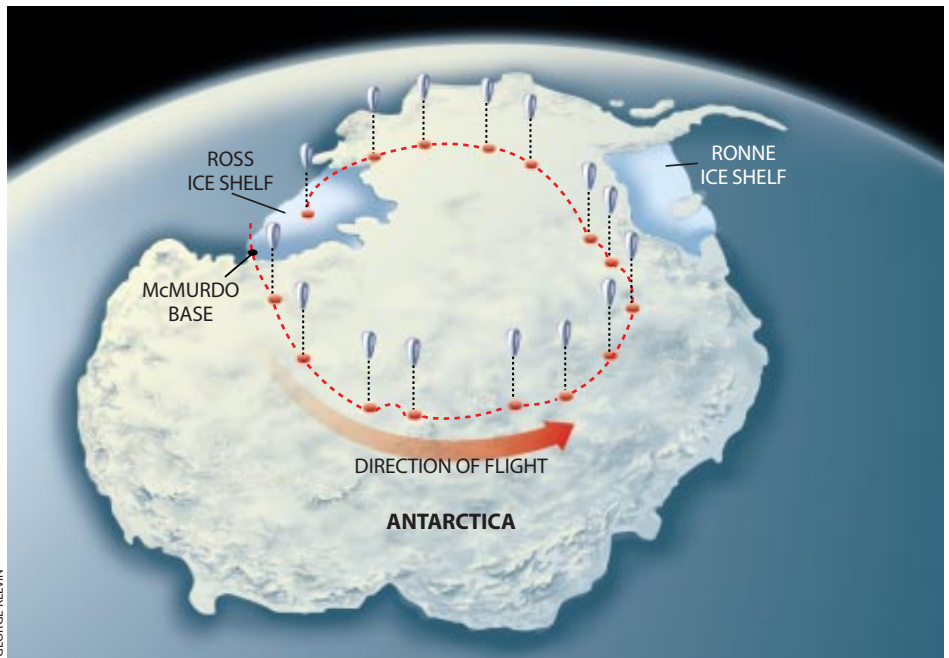
HIGH-ALTITUDE BALLOON launched near McMurdo Base in Antarctica carries cosmic-ray detectors above most of the atmosphere. Winds 40 kilometers above the ice cap blow in a circle around the Pole, returning the balloon to the vicinity of its starting point after about 10 days. Balloon detectors are not as sensitive as those placed on board satellites, but they can be made much larger and lofted much more cheaply.

mous effective areas for months or years. The information, however, must be extracted from cascades of secondary particles—electrons, muons and gamma rays—initiated high in the atmosphere by an incoming cosmic-ray nucleus. Such indirect methods can only suggest general features of the composition of a cosmic ray on a statistical basis, rather than identifying the atomic number of each incoming nucleus.

At ground level, the millions of secondary particles unleashed by one cosmic ray are spread over a radius of hundreds of meters. Because it is impractical to blanket such a large area with detectors, the detectors typically sample these air showers at a few hundred or so discrete locations.

Technical improvements have enabled such devices to collect increasingly sophisticated data sets, thus refining the conclusions we can draw from each shower. For example, the CASA-MIA-DICE experiment in Utah, in which two of us (Cronin and Swordy) are involved, measures the distributions of electrons and muons at ground level. It also detects Cerenkov light (a type of optical shock wave produced by particles moving faster than the speed of light in their surrounding medium) generated by the shower particles at various levels in the atmosphere. These data enable us to reconstruct the shape of the shower more reliably and thus take a better guess at the energy and identity of the cosmic ray that initiated it.

The third one of us (Gaisser) is working with an array that measures showers reaching the surface at the South Pole. This experiment works in conjunction with AMANDA, which detects energetic muons produced in the same showers by observing Cerenkov radiation produced deep in the ice cap. The primary goal of AMANDA is to catch traces of neutrinos produced in cosmic accelerators, which may generate upward-streaming showers after passing through the earth.



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In addition to gathering better data, researchers are also improving detailed computer simulations that model how air showers develop. These simulations help us to understand both the capabilities and the limitations of ground-based measurements. The extension to higher energies of direct cosmic-ray detection experiments, which allows both ground-based and airborne detectors to observe the same kinds of cosmic rays, will also help calibrate our ground-based data.

Rare Giants

Cosmic rays with energies above 10^{20} eV strike the earth's atmosphere at a rate of only about one per square kilometer a year. As a result, studying them requires an air-shower detector of truly gigantic proportions. In addition to the 1991 event in Utah, particles with energies above 10^{20} eV have been seen by groups elsewhere in the U.S., in Akeno, Japan, in Haverah Park, U.K., and in Yakutsk, Siberia.

Particles of such high energy pose a conundrum. On the one hand, they are likely to come from outside our galaxy because no known acceleration mechanism could produce them and because they approach from all directions even though a galactic magnetic field is insufficient to bend their path. On the other hand, their source cannot be more than about 30 million light-years away, because the particles would otherwise lose energy by interaction with the universal microwave background—radiation left

over from the birth of the cosmos in the big bang. In the relativistic universe that the highest-energy cosmic rays inhabit, even a single radio-frequency photon packs enough punch to rob a particle of much of its energy.

If the sources of such high-energy particles were distributed uniformly throughout the cosmos, interaction with the microwave background would cause a sharp cutoff in the number of particles with energy above 5×10^{19} eV, but that is not the case. There are as yet too few events above this nominal threshold for us to know for certain what is going on, but even the few we have seen provide us with a unique opportunity for theorizing. Because these rays are essentially undeflected by the weak intergalactic magnetic fields, measuring the direction of travel of a large enough sample should yield unambiguous clues to the locations of their sources.

It is interesting to speculate what the sources might be. Three recent hypotheses suggest the range of possibilities: galactic black-hole accretion disks, gamma-ray bursts and topological defects in the fabric of the universe.

Astrophysicists have predicted that black holes of a billion solar masses or more, accreting matter in the nuclei of active galaxies, are needed to drive relativistic jets of matter far into intergalactic space at speeds approaching that of light; such jets have been mapped with radio telescopes. Peter L. Biermann of the Max Planck Institute for Radioastronomy in Bonn and his collaborators



STEVEN PETERZEN National Scientific Balloon Facility

Whatever the source of these cosmic rays, the challenge is to collect enough of them to search for detailed correlations with extragalactic objects. The AGASA array in Japan currently has an effective area of 200 square kilometers, and the new Fly's Eye HiRes experiment in Utah will cover about 1,000 square kilometers. Each detector, however, can capture only a few ultrahigh-energy events a year.

For the past few years, Cronin and Alan A. Watson of the University of Leeds have been spearheading an initiative to gather an even larger sample of ultrahigh-energy cosmic rays. This development is named the Auger Project, after Pierre Auger, the French scientist who first investigated the phenomenon of correlated showers of particles from cosmic rays. The plan is to provide detectors with areas of 9,000 square kilometers that are capable of measuring hundreds of high-energy events a year. A detector field would consist of many stations on a 1.5-kilometer grid; a single event might trigger dozens of stations.

An Auger Project design workshop held at the Fermi National Accelerator Laboratory in 1995 has shown how modern off-the-shelf technology such as solar cells, cellular telephones and Global Positioning System receivers can make such a system far easier to construct. A detector the size of Rhode Island could be built for about \$50 million. To cover the entire sky, two such detectors are planned, one each for the Northern and Southern hemispheres.

As researchers confront the problem of building and operating such gigantic detector networks, the fundamental question remains: Can nature produce even more energetic particles than those we have seen? Could there be still higher-energy cosmic rays, or are we already beginning to detect the highest-energy particles our universe can create? SA

suggest that the hot spots seen in these radio lobes are shock fronts that accelerate cosmic rays to ultrahigh energy. There are some indications that the directions of the highest-energy cosmic rays to some extent follow the distribution of radio galaxies in the sky.

The speculation about gamma-ray bursts takes off from the theory that the bursts are created by relativistic explosions, perhaps resulting from the coalescence of neutron stars. Mario Vietri of the Astronomical Observatory of Rome and Eli Waxman of Princeton University independently noted a rough match between the energy available in such cataclysms and that needed to supply the observed flux of the highest-energy cosmic rays. They argue that the ultrahigh-speed shocks driven by these explosions act as cosmic accelerators.

Perhaps most intriguing is the notion that ultrahigh-energy particles owe their existence to the decay of monopoles,

strings, domain walls and other topological defects that might have formed in the early universe. These hypothetical objects are believed to harbor remnants of an earlier, more symmetrical phase of the fundamental fields in nature, when gravity, electromagnetism and the weak and strong nuclear forces were merged. They can be thought of, in a sense, as infinitesimal pockets preserving bits of the universe as it existed in the fractional instants after the big bang.

As these pockets collapse, and the symmetry of the forces within them breaks, the energy stored in them is released in the form of supermassive particles that immediately decay into jets of particles with energies up to 100,000 times greater than those of the known ultrahigh-energy cosmic rays. In this scenario the ultrahigh-energy cosmic rays we observe are the comparatively sluggish products of cosmological particle cascades.

The Authors

JAMES W. CRONIN, THOMAS K. GAISSER and SIMON P. SWORDY work on both the theoretical questions of how cosmic rays are created and the practical problems inherent in detecting and analyzing them. Cronin, a professor of physics at the University of Chicago since 1971, earned his master's degree from the university in 1953 and his doctorate in 1955. In 1980 he shared the Nobel Prize with Val L. Fitch for work on symmetry violations in the decay of mesons. Gaisser, a professor of physics at the University of Delaware, has concentrated on the interpretation of atmospheric cosmic-ray cascades; he earned his doctorate from Brown University in 1967. In 1995 Gaisser spent two months in Antarctica setting up cosmic-ray detectors. Swordy, an associate professor at Chicago, has been active in cosmic-ray measurement since 1976. He earned his Ph.D. from the University of Bristol in 1979.

Further Reading

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