Catching Some Rays

Earth-based detectors hunt for violent stellar events

By RON COWEN

At Los Alamos National Laboratory, fiberglass cones await the arrival of particles from a cosmic-ray shower. Each cone, part of an experiment called CYGNUS, contains a plastic sheet that scintillates when a particle strikes it; a phototube at the top of each cone senses the faint burst of light.

Goodman

It's a moonless night as dozens of garbage-can-shaped devices face the sky from a desert bluff in central Utah. Each of these mirrored sentinels waits to witness a dim blue flash – leftover energy from some of the most violent collisions in our galaxy and beyond.

This array of instruments is just one of many that search for the telltale fingerprints left by cosmic rays penetrating Earth's atmosphere. At energies of up to 100 billion billion electron-volts, cosmic rays rain upon our planet from the depths of the Milky Way and from stars hundreds of thousands of light-years beyond.

The rays come in two varieties. Most are charged particles (ions), while a tiny minority encompass energetic, uncharged particles of light – photons called gamma rays. Believed to be created during such cataclysmic events as supernova explosions and galactic collisions, both types of cosmic rays represent, quite simply, the most energetic particles in the universe.

Since the 1980s, several types of ground-based detectors – most of them surprisingly simple in design – have detected cosmic rays one million times more energetic than any generated by the world's most powerful atom smasher – the Fermi National Accelerator Laboratory's tevatron particle accelerator in Batavia, Ill. Indeed, notes University of Chicago physicist Leslie J. Rosenberg, searching for cosmic rays – particularly high-energy gamma rays – is now uniting astronomers and particle physicists in a common pursuit.

"The study of astrophysical sources has traditionally been the exclusive domain of astrophysics," he notes. "Particle production and decays have traditionally been the exclusive domain of particle physics . . . [But] at sufficiently high energies, particle production and decays become prominent features of astrophysical sources, and the two fields of study intertwine."

In fact, since 1988 researchers have puzzled over observations that suggest very-high-energy gamma rays have properties similar to energetic ions. Findings from several independent research groups all suggest that new physical phenomena may emerge at high energies – either an elementary particle never before discovered or unexpected behavior by photons (SN: 10/29/88, p.276).

Gamma rays make up less than one-hundredth of 1 percent of all high-energy cosmic rays, particles associated primarily with such exotic objects as neutron stars, supernovas, quasars, exploding galaxies and the long-sought black holes. But scientists say that searching for gamma rays has a distinct advantage. Most charged cosmic rays form a diffuse, uniform background that offers few clues to the site of their stellar or galactic birthplaces. The straight-line path of gamma rays more readily indicates their precise origin (see box on p. 297).

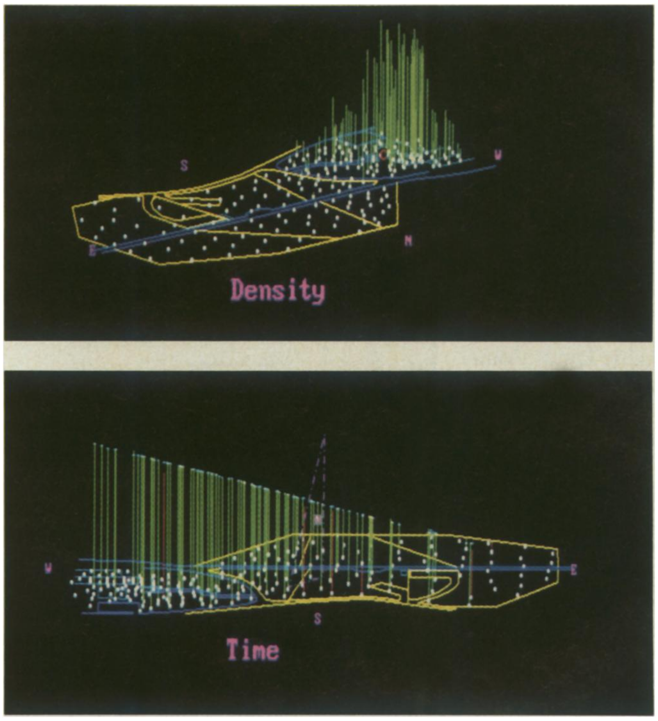
Cosmic-ray investigators caution that after nearly two decades of observations, they have pinpointed only a few possible sources of energetic gamma rays. "The field of ultra-high-energy gamma-ray astronomy is in its infancy," declares Jordan A. Goodman of the University of Maryland at College Park. But if new, more sensitive detectors can verify the 1988 reports from the Whipple Observatory near Amado, Ariz., the Haleakala Gamma Ray Observatory in Hawaii and the CYGNUS experiment at Los Alamos (N.M.) National Laboratory, scientists may find themselves grappling with a cosmic mystery: why high-energy gamma rays begin to masquerade as charged cosmic rays.

The Gamma Ray Observatory, launched April 6, may further spark interest in ground-based gamma-ray studies. Carrying the four largest scientific instruments ever flown in space, this orbiting observatory promises to reveal a myriad of new findings over its anticipated four-year life. Its quest includes the search for telltale radiation from such exotic objects as pulsars, quasars and black holes (massive objects believed to exist but never yet detected). The orbiting laboratory will also attempt to measure the balance between matter and antimatter in the universe. Moreover, the observatory's location above Earth's atmosphere enables its instruments to directly detect gamma rays, rather than having to infer their presence from secondary particles.

Like all space-borne technology, however, this observatory has limitations: It can study only "medium-energy" gamma rays – those with energies up to 10 billion electron-volts (10 GeV). Particles generated close to a neutron star, a rapidly spinning binary-star system, or other seat of celestial power may have even higher energies – a discriminating characteristic of the universe's most violent territories. But at energies greater than about 10 billion GeV, the rain of photons and charged particles they emit slows to a trickle. The limited collecting area of space-orbiting devices therefore makes detection of them all but impossible.

Trevor C. Weekes of the Whipple Observatory and other researchers hope, however, that findings from the new orbiting observatory will uphold an old adage: Where there's smoke, there's fire. These scientists hope that the observatory's expected discovery of several hundred new medium-energy gamma ray sources may identify areas of the sky likely to emit higher-energy photons – gamma rays whose presence can be inferred only from Earth.

Observes Weekes: "By a happy accident of nature, just where space-borne detectors become impractical, ground-based techniques, which use Earth's atmosphere as the detection medium, become feasible."



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At top, data from a cosmic-ray shower recorded by the CYGNUS experiment in June 1990 show that only some of the detectors (denoted by black dots) sensed incoming particles (denoted by green lines). At bottom, a display of the time order in which each detector recorded a signal reveals the path taken by the incoming particles. Researchers use such paths to trace the celestial source of the particle's parent gamma rays.

Progress in cosmic-ray physics has proven slow since the field's birth in 1911. Nonetheless, for the first several decades, "catching some rays" proved a riveting adventure.

The quest for cosmic rays began in western Europe. Father Theodor Wulf, a Jesuit priest and amateur scientist in Paris, set up a pioneering experiment atop the Eiffel Tower. In Austria, a young physicist named Victor Hess ascended several miles in a hot air balloon. Working independently, both men succeeded in their goal: the first evidence for particles later dubbed cosmic rays.

Laboratory experiments had previously demonstrated that energetic radiation strips electrons from atoms in a gas, permitting these ionized atoms to conduct electricity. Relying on this phenomenon, Hess and Wulf probed the atmosphere with an electroscope, two thin gold leaves suspended from a common point inside a gas-filled, electrically insulated container. An electric charge initially stored on the surface of the leaves causes them to repel each other and move apart; but as incoming radiation ionizes gas inside the electroscope, the charge leaks away and the leaves come back together. The faster the leaves return to their original position, the stronger the radia-

Cosmic Rain Gauges

Bent, kicked and accelerated by galactic magnetic fields, a typical charged cosmic ray travels a zig-zag path for millions of years before striking Earth's atmosphere. Such meandering particles—mostly hydrogen ions—have no "memory" of the violent, highly energetic collisions that spawned them.

Not so gamma rays. Born in the same violent reactions, these cosmic-ray photons carry no charge, and therefore cannot be deflected by magnetic or electric fields.

Traveling in a straight line from their source, the path of gamma rays indicates the nature and location of the cataclysmic events that created them. Physicists believe that many of the highest energy gammas derive from charged particles, such as energetic protons near a rapidly rotating star system. When these particles slam into other charged particles, another class of elementary particles – neutral pions – are born. Neutral pions rapidly decay into gamma rays.

Only space-borne detectors, such as those aboard NASA's Gamma Ray Observatory, can directly catch these photons, since any gammas able to penetrate the Earth's atmosphere rapidly self-destruct, forming other particles. However, space-borne instruments are usually limited to recording rays with energies smaller than about 10 billion electron volts (10 GeV). The dramatically lower abundance of gammas with higher energies allows most to elude the relatively small collecting area of orbiting detectors.

Fortunately, these higher energy gammas *do* penetrate Earth's atmosphere. Their interaction with gas molecules there generates charged secondary particles and an air shower of photons that can be detected with large, ground-based instruments.

In order of ascending energies, physicists classify gammas that penetrate the atmosphere into three categories: very-high-energy (100 to 100,000 GeV), ultra-high energy (10^5 to 10^7 GeV) and extremely high energy (10^8 to 10^{11} GeV).

As they die out in the atmosphere, extremely high-energy gamma rays (and similarly energetic charged cosmic rays) excite nitrogen atoms to fluoresce. Mirrored detectors trained on the night sky can infer the existence of such gammas from a telltale flash of blue light and attempt to pinpoint their source.

In contrast, ultra-high-energy gamma rays don't incite much fluorescence. But they do undergo fatal interactions with the atmosphere at an altitude of about 20 kilometers, generating a falling cascade of charged particles. These particles eventually fan out to shower a large pancake-shaped area of Earth's surface. With arrays of plastic scintillators on the ground, astronomers can not only "observe" the charged particles but also infer the location and incoming angle of their parent gamma rays.

For slightly less energetic gammas, those in the very-high-energy range, ground-based arrays of particle detectors prove useless, because the atmosphere absorbs all of the charged secondary particles. Before these secondaries vanish, however, the speedy particles emit a visible bluish-white light, known as Cerenkov radiation, along the direction of motion. Specially equipped ground-based telescopes seek out these Cerenkov flashes that signal the annihilation of very-high-energy gamma rays. *– R. Cowen* tion source.

Taking his electroscope aloft, Hess found that above 5,000 feet, the radiation steadily increased its intensity – to several times ground levels at 17,500 feet, the maximum altitude of the physicist's balloon. This "extra-terrestrial source of penetrating radiation," as Hess termed it, represented the first evidence of cosmic rays.

Throughout the 1930s and 1940s, scores of young physicists scaled mountaintops in an effort to record ever higher energy cosmic-ray showers striking Earth. Some of the scientists braved blizzards, and a few froze to death trying to capture the shower of high-speed atomic nuclei generated by cosmic rays. Their rewards included the discovery of a new zoo of elementary particles: kaons, pions and muons.

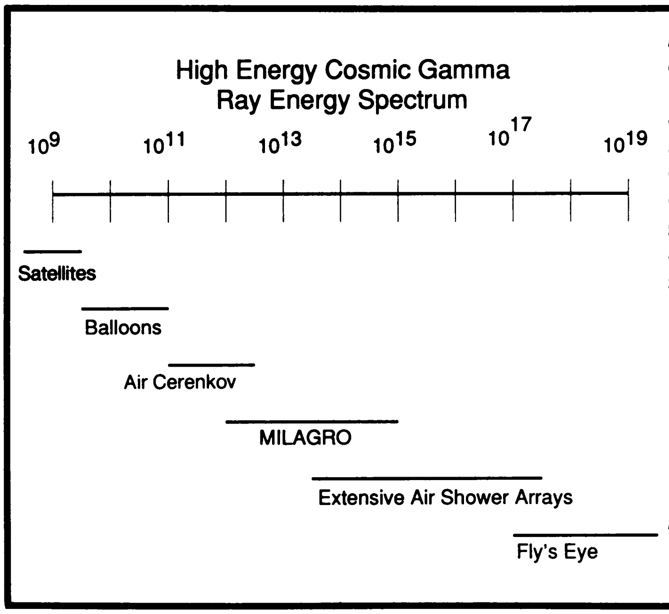
In the following decades, most high-energy physicists switched their allegiance from the heavens to the laboratory as particle accelerators – highly efficient generators of energetic particles – became standard research tools. Why study the unpredictable cosmic rain when a researcher could make as many high-energy particles as desired, and with just the right energy, inside a heated building?

Beginning in the 1970s, gamma-ray astronomy launched a comeback. The few diehards who had never abandoned their cosmic-ray studies reported finding many particles at energies far higher than accelerators could produce. Scientists once again turned skyward, searching for gamma rays.

These studies required several types of instruments. None directly detects the rays, since the photons self-destruct to form pairs of oppositely charged ions some 20 kilometers above Earth's surface. But the variety of devices, each tailored to track the activity of gamma rays of different energy, share a common principle: They wait to see the light.

For example, 67 cylindrical detectors, each outfitted with a large mirror that focuses light onto several photomultiplier tubes, sit atop a hill at the Army's Dugway (Utah) Proving Ground. Every detector surveys a different portion of the night sky, waiting for a faint bluish glow – the hallmark of 10^8 to 10^{11} GeV particles, the most energetic cosmic rays known. A fluorescence signals their collision with nitrogen atoms in the air.

Two miles away, a smaller array of identical detectors stands at attention, recording atmospheric fluorescence from atoms at up to 10 kilometers altitude. Designed at the University of Utah in Salt Lake City and known as Fly's Eye I and II, the multi-mirror arrays, which can operate only on dark, moonless nights, emulate the compound character of insect eyes. Together, the two detectors help distinguish signals produced by cosmic gamma rays from spurious light emitted by nearby sources.



Goodman

Energy spectrum of gamma rays (in electron-volts). Satellites and balloons directly detect the rain of lower-energy gammas. But the relative scarcity of gammas of higher energies requires the larger area of an assortment of ground-based instruments, which indirectly infer the existence of these rays from decay particles produced in the atmosphere.

Several other detectors at the Dugway site detect lower-energy gamma rays. A collection of 1,089 plastic scintillators surround Fly's Eye II. A project completed last month by the University of Chicago and known as the Chicago Air Shower Array, these detectors cover 250,000 square meters – the largest grouping of their kind in the world. Night and day, they record cosmic showers induced by gamma rays a few notches down in energy from those detected by Fly's Eye – about 10^5 to 10^7 GeV.

Though not energetic enough to make nitrogen glow, these gamma rays do induce a cylindrically shaped stream of charged secondary particles that induce a flash when they strike the plastic scintillators. The incoming angle and intensity of this shower helps astronomers pinpoint the celestial source of the gamma rays.

Buried three meters below the Dugway site lies yet another group of instruments, this set designed by researchers at the University of Michigan in Ann Arbor. The 16 underground detectors count muons – elementary particles that resemble heavier versions of the electron – during cosmic-ray showers. A relative paucity of muons indicates that a gamma ray likely induced the particle shower detected above ground; an abundance of muons suggests charged cosmic rays created the shower.

Surveying gamma rays at the same energies as the Chicago array, a set of 202 scintillators spreads over 85,000 square meters atop a plateau at Los Alamos National Laboratory. Known as CYGNUS, this joint venture of research groups from Los Alamos, Argonne (Ill.) National Laboratory, the University of Maryland at College Park, the University of California in Irvine and Santa Cruz, and George Mason University in Fairfax, Va., also includes muon detectors buried under six feet of concrete.

Goodman notes that the proximity of the University of Chicago scintillators in Utah to the CYGNUS experiment may have a special payoff: "If you have two experiments observing the same sky, the same source, at the same time, you can't attribute a finding to a mere statistical fluctuation."

About 880 kilometers away from Los Alamos, perched atop Mount Hopkins in southern Arizona, lies another type of detector, sensitive to the lowest-energy gamma rays that can be indirectly detected on Earth.

On clear, moonless nights, a 10-meter-wide dish of 248 mirrors on this mountaintop focuses incoming light onto a cluster of 109 photomultiplier tubes. This Whipple Observatory telescope, like several other similar instruments around the world, infers the presence of gamma rays at slightly lower energies – 100 to 10,000 GeV – from a telltale, forward-directed beam of extremely faint light several hundred meters in diameter and about one meter thick.

Analogous to a shock wave, this light, called Cerenkov radiation, appears when the speed of particles exceeds that of light in the medium through which they're moving. Because the particles emit light along their direction of motion, scientists can trace their path and that of their parent gamma rays.

In fact, reconstructing the path of gamma rays has, not surprisingly, proven a primary focus of these studies. By determining the rapid time order – a matter of nanoseconds – in which detectors in a large array receive a signal, investigators can calculate the angle at which a cosmic ray collided with the atmosphere, as well as its point of origin.

Using such ground-based detectors, researchers have found several likely gamma-ray sources. The most convincing data, Rosenberg says, come from Whipple Observatory scans of the Crab pulsar, part of the Crab nebula. Using the Cerenkov telescope, Weekes and his colleagues identified a region near this isolated X-ray-pulsing neutron star three years ago that appears to emit 1,000 GeV gamma rays.

Rosenberg notes that the researchers found a steady gamma-ray signal from the Crab at widely separated times and no evidence that these emissions varied with the Crab's X-ray pulsing interval of 33 milliseconds. While these data suggest that gamma rays may not emanate from the pulsar itself, he says the Crab nonetheless represents the only undisputed source of high-energy gamma rays.

Goodman and other researchers have speculated about what type of violent collisions might trigger the production of these gamma rays. Physicists believe that high-energy gamma rays occur as a byproduct of particularly violent collisions between protons and other charged particles. But in the isolated Crab – a single neutron star surrounded by nearly empty space – it's hard to see what other charged particles protons could collide with, Goodman says.

Instead, he suggests, a process called inverse Compton scattering may account for the gamma rays. In this scenario, a beam of high-energy electrons traveling at nearly the speed of light collides with ordinary X-rays emitted by the star. The electrons impart nearly all their energy to the photons, transforming the X-rays to gamma rays. Goodman says if his theory about the origin of these photons proves correct, the number of gammas above 100,000 GeV should begin to fall, since Compton scattering cannot produce photons at these higher energies.

Indications that gamma rays also emerge from Cygnus X-3, an X-ray-emitting binary star system, appear less compelling. In 1979, Soviet researchers at the Crimean Astrophysical Observatory in Nauchny reported finding that this star system – consisting of a neutron star and a lower-mass companion about 30,000 light-years from Earth – appear to emit 10,000 GeV gamma rays. Four years later, investigators using scintillation detectors at the University of Kiel in Germany also saw evidence for energetic gamma-ray bursts near this binary system.

Some researchers speculate that matter drawn from the lower-mass companion and falling onto a hot disk surrounding the neutron star may accelerate fast enough to produce very-high-energy protons and gamma rays. But more recent observations showed no excess of cosmic rays from this stellar pair. Though some investigators now question the validity of the earlier reports, Rosenberg notes that others interpret the data to suggest that Cygnus X-3's gamma emissions may be on the wane.

"If you're a pessimist, you say the previous results were a statistical fluctuation; if you're an optimist you say that previously the source was on, now the source is off," explains physicist Eugene C. Loh of the University of Utah, a researcher with the Fly's Eye experiments.

Cygnus X-3 observations at even higher energies offer similarly contradictory interpretations. For instance, while several decades of data collected by the Fly's Eye experiments and a similar airglow study at the Akeno (Japan) Cosmic Ray Observatory suggest X-3 may emit 10^9 GeV gamma rays, a 1989 air shower observed by detectors at Havarah Park, England, showed no such evidence.

The most controversial – and potentially exciting – observations involve Hercules X-1, another binary system possessing a neutron star. During 1986, separate teams of researchers working at the CYGNUS project, at the Whipple Observatory, and at the Haleakala Gamma Ray Observatory in Maui, Hawaii, independently reported signs of mysterious cosmic-ray bursts that maintained a period just slightly shorter than the neutron star's X-ray pulsing cycle.

Several lines of evidence suggested the pulses stemmed from high-energy gamma rays. For example, the tightly focused beam apparently had traveled in a straight line and carried no charge. But data from the underground detectors at Los Alamos confounded this explanation: They showed the particle shower possessed far more muons than gamma rays normally create.

Several possibilities, none fitting accepted theories about matter, could explain the mystery, Rosenberg says. Photons at high energies might behave more like protons or other particles with mass – interacting strongly with atomic nuclei in the upper atmosphere to produce muons. Alternatively, the beam might have contained an unusual type of massive neutrino – neutral particles generally assumed to have no mass, but whose gravitational properties remain uncertain.

The debate over the data continues, involving both astronomers and particle physicists. "To be very candid, nobody understands what's going on and nobody is even convinced, at this stage, that they've observed these damn things," says Goodman. "There's enough controversy in the field now that people aren't 100 percent happy with anything."

While many issues remain unresolved, ground-based cosmic-ray astronomy continues to thrive. In addition to the recently completed Chicago Air Shower Array, other gamma-seeking arrays are planned at the Las Palmas Observatory in the Spanish Canary Islands, and near Lhasa, Tibet.

Cosmic-ray physics is also evolving into a fluid endeavor. Goodman says his CYGNUS group proposes to detect gamma rays with a pond in the Jemez mountains of northern New Mexico. The researchers plan to divide the pond, 8,700 feet above sea level, into two horizontal sections. Detectors submerged in the top half will search for cosmic rays, while devices lying near the bottom will record neutrinos in an attempt to help discriminate charged cosmic rays from gammas. Some 600 photomultiplier tubes immersed 1.5 meters below the pond's surface will act as Cerenkov detectors, recording any light that particles from cosmic air showers produce as they pass through the water.

Unlike Cerenkov detectors above water, these detectors can operate night and day, thanks to a light-tight cover that will blanket the pond. "To look for these [gamma-ray outburst] episodes, you need a powerful detector that's on all the time," Goodman says.

A series of round-the-clock muon detectors will operate under another light-tight cover, in the lower layer, eight meters beneath the pond's surface. Eventually, says Goodman, his group hopes to move its CYGNUS project from Los Alamos to the perimeter of this pond.

His CYGNUS group has already begun to adopt aquatic technology with the purchase of several backyard swimming pools. One, filled with water and light detectors, now sits alongside CYGNUS at Los Alamos. Goodman says this pooling of detectors should improve the angular resolution of CYGNUS' scintillators, helping to better pinpoint the direction of cosmic gamma sources.

Researchers have also begun work on a new, triangular version of the Fly's Eye. Each of its three "eyes," spaced 15 kilometers apart, will contain a network of 54 mirrors two meters in diameter. Loh's team already has a working prototype and expects completion of the entire project within four years.

"The reason we're not frustrated is that we know cosmic rays are coming at a steady rate," Loh says. "It's not like somebody decides they're going to turn off your laboratory experiment before you're ready. . . . If you're good at it, you're bound to catch them."

Loh adds that his group has plenty to do – including better characterization of extragalactic sources – even if the origin of cosmic rays remains a mystery for some time to come. Regardless of the pace of new discoveries, he says, radiation associated with the powerful collisions and violent accelerations of deep space will provide researchers with a continuing tale of adventure and suspense. ☐