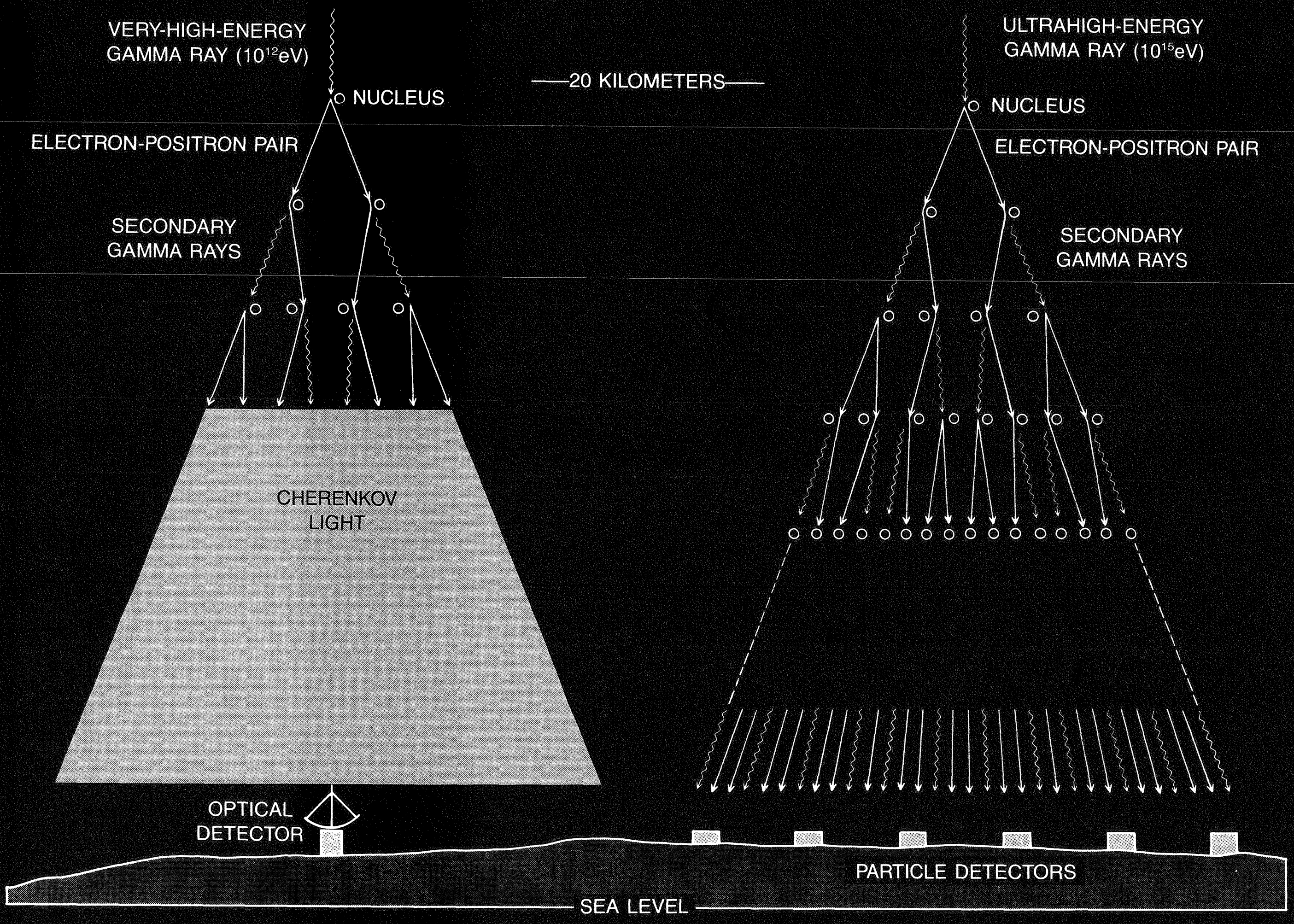
GAMMA-RAY ASTRONOMY

The High-Energy Universe

by Marcia Bartusiak



By expanding their observations into the high-energy-gamma portion of the electromagnetic spectrum, astronomers and physicists have opened a new window to the cosmos.

Detecting gamma rays. At very high energies (left), only blue-tinged Cherenkov light, triggered by secondary gamma particles, can be seen. At ultrahigh energies (right), the secondary particles themselves survive.

"When I began working in astronomy in 1933," recalls Harvard astronomer Leo Goldberg, "astronomy was almost strictly an observational science with very little understanding of the physical meaning of observations. . . . The universe was a quiet and peaceful place, slowly evolving and exhibiting little of the violent and explosive behavior that we now take for granted." In the succeeding years, Goldberg has seen astronomy expand like the universe itself, "driven by a sequence of technological and scientific advances and by a tenfold growth in the number of astronomers."

In recent time, astronomy's most dramatic discoveries have occurred whenever observers opened previously unexplored regions of the electromagnetic spectrum, beyond the narrow portion available to human vision. Arrays of radio antennas spread over entire countrysides, for example, have allowed astronomers to see young galaxies, situated in the farthest reaches of the universe, spew from their central cores the energy of a trillion suns. Similarly, X-ray telescopes, orbiting beyond the blocking effects of the earth's atmosphere, have watched 20-kilometer-wide neutron stars—the collapsed remnants of massive stars—spin dozens to hundreds of times each second.

Ground- and space-based instruments now scan the sky in infrared, ultraviolet, and gamma-ray bands as well. It might appear as if astronomy had run out of fresh portions of the electromagnetic spectrum to exploit. Yet the most energetic radiations coursing through the universe have remained frustratingly elusive. These are gamma rays whose energies equal or exceed a trillion electron volts (a trillion times the energy of visible-light photons)—emanating from sources both within and beyond the Milky Way. The length of such high-energy waves measures less than 10^{-16} centimeter; a thousand such waves could easily span a single proton.

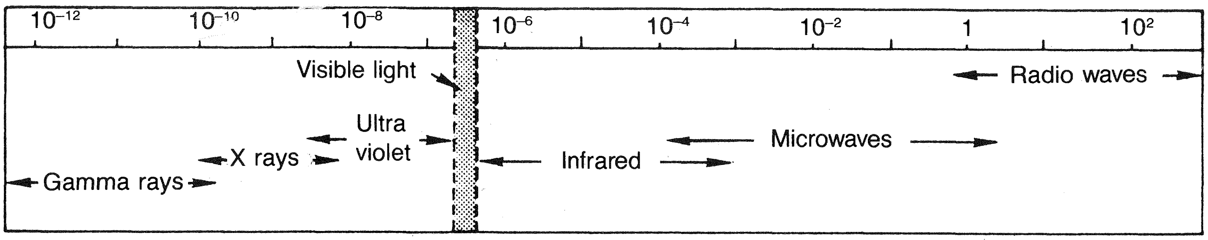
To differentiate these power-packed photons from the more ordinary lower-energy gamma rays, astronomers generally refer to them as VHE (very-high-energy, in the range of 10^{11} to 10^{14} eV) and UHE (ultra-high-energy, greater than 10^{14} eV). At times, they are also known as *TeV* (for tera- or 10^{12} eV) and *PeV* (for peta- or 10^{15} eV).

Photons at these energies, according to Trevor Weekes, a 20-year veteran in this struggling but burgeoning field, "are the true messengers of high-energy astrophysics; they cannot be produced other than in extremely high-energy interactions."

Weekes and his colleagues share the same aspiration: to unravel the secrets of nature's most efficient and awesome particle accelerators—exotic black holes, binary neutron-star systems, supernovas, and explosive quasars—whose underlying mechanisms could conceivably be studied effectively with high-energy gamma-ray detectors. As a consequence, VHE and UHE gamma-ray astronomy holds forth the promise of solving one of science's most vexing mysteries: the true origin and nature of cosmic rays, those highly energetic charged particles that stream through space and continuously bombard the earth. "For many high-energy astrophysicists," says Weekes, "this is the outstanding challenge. We can accelerate particles here on earth to a few trillions of electron volts; but forces in the universe can accelerate them to energies 10 million times as great. It's quite possible that unknown physical processes are involved."

Early start-up

Oddly, interest in gathering high-energy gamma rays originated even before X-ray astronomy got under way. As early as 1948, Eugene Feenberg and Henry Primakoff (then at Washington University in St. Louis) reported that photons traveling through interstellar space are expected to occasionally bump into speeding electrons and—in the course of the interaction—be boosted to gamma-ray energies, a process known as Compton scattering. More persuasive was a seminal paper written by MIT physicist Philip Morrison in 1958, in which Morrison outlined a number of gamma-ray-emitting events expected to occur throughout the galaxy and the universe. For instance, whenever an



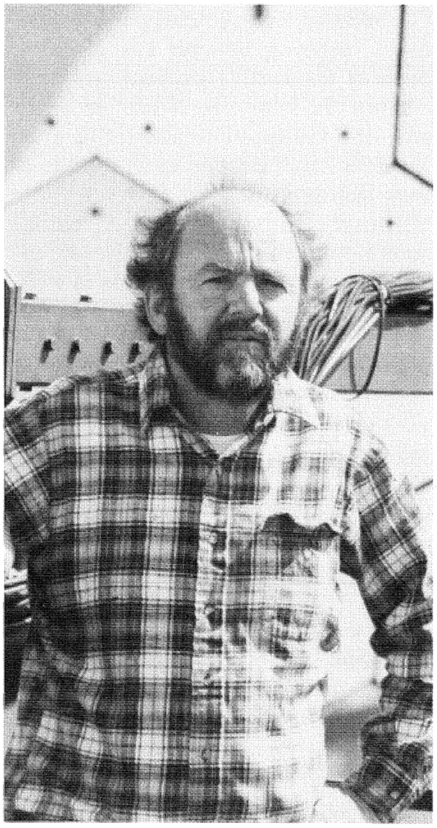
Electromagnetic spectrum. Gamma rays are the most energetic—and the most elusive—of all wavelengths.

electron meets its antimatter mate the positron, the two particles will annihilate, creating a distinctive gamma-ray signal with a half-million electron volts of energy. Earlier, Hideki Yukawa had pointed out that the decay of neutral pimesons or pions, short-lived particles produced in cosmic-ray collisions with matter, would emit gamma rays with characteristic energies. Such predictions led astronomers to begin thinking about gamma-ray observations. (See "The lower end of the gamma-ray street" accompanying this article.)

By the 1960s, other theorists were suggesting that young, energetic supernova remnants, such as the famous Crab nebula (the remains of a stellar explosion sighted in 1054 A.D.), would be particularly noticeable in the VHE gamma-ray region. This expectation motivated groups in the Soviet Union, the British Isles, and the United States to search specifically for these high-energy photons. "It was the lure of breaking into an entirely new energy range, one that hadn't been mined," recalls Jonathan Grindlay, an X-ray astronomer who is now with the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts but who was a devoted TeV astronomer during his graduate-school days.

A special optical technique, developed in the early 1950s by British physicists John V. Jelley and William Galbraith to view cosmic-ray showers, provided the means of detecting the VHE gamma rays. Observations in the gamma-ray region are usually conducted by lofting instruments high above the gamma-ray-absorbing atmosphere, aboard balloons, rockets, and satellites. Such an approach is not feasible for detecting gamma rays in the TeV range and above, however; VHE gamma rays are simply too scarce. A meter-wide spaceborne detector might capture only one TeV photon each year. But, as Jelley had proposed, the earth's atmosphere itself, which is far vaster in total surface area, can act as a single, giant detector.

Whenever a VHE gamma ray, or a cosmic-ray particle, strikes the atmosphere, at an altitude of about 20 kilometers, it generates a shower of secondary elementary particles that is strongly beamed in the forward direction. As these particles plummet downward, though before being absorbed by the atmosphere, they trigger the release of a brief flash of bluish light known as Cherenkov radiation, named for its discoverer, the Russian physicist Pavel Cherenkov. The faint, nanoseconds-long light burst—too fast to be visible to the naked eye—is emitted because electrons in the atmosphere are disturbed by the passage of the newly created particles, which are moving at velocities faster than the speed of light in air.



Weekes. A twenty-year gamma-ray veteran.

"The Cherenkov light arrives at the earth's surface as a sort of pancake, some hundreds of meters in diameter and about a meter thick," explains Weekes. Thus, even though the original VHE gamma ray is not collected directly, it can be spotted and tracked via its Cherenkov signature.

The ten-meter reflector

In the early 1960s, two independent groups—one of Soviet scientists and one a British-Irish collaboration of which Weekes was a member—made the first serious attempts to detect these gamma-ray-induced flashes, using old searchlight mirrors. During these initial tests nothing of consequence was found, but soon a more ambitious effort was launched in the United States.

Intrigued by the potential of TeV astronomy, in 1967 Giovanni Fazio of the Smithsonian Astrophysical Observatory began an effort to erect a ten-meter reflector at the Smithsonian's field installation (now known as the Fred Lawrence Whipple Observatory) atop Mount Hopkins in southern Arizona. Perched on the edge of a 2.3-kilometer-high ridge just below the mountain's peak, the giant dish (which somewhat resembles a radio telescope) consists of 248 separate hexagonal mirrors that together act as a large light bucket for Cherenkov radiation.

Weekes, who had moved from Ireland to join the Smithsonian team, recalls that the mirrored surface originally focused the Cherenkov light on a single photomultiplier tube. "There would be a flash of light," he says, "and we would record a count." On a good night, a VHE gamma-ray detector observes about three events each second.

Progress was slow. In 1973, after years of observations, the group was at last able to announce having detected gamma rays with energies of 10^{11} electron volts emanating from the Crab nebula. This discovery confirmed the fact that high-energy electrons were indeed spiraling about in the chaotic magnetic fields of the supernova remnant.

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"When I joined the group as a Harvard graduate student in 1969," adds Grindlay, "the evidence was tantalizing, but marginal, for we were always fighting a vicious background [of radiation noise]." In the case of the Crab nebula, the gamma-ray-induced flashes were distinguished only after months of measurements, because for every flash of Cherenkov light generated by a VHE gamma ray, roughly a thousand bursts are triggered by incoming cosmic-ray particles.

Winnowing wheat from chaff in this range exploits a phenomenon that distinguishes gamma events from their background. After some time, the Cherenkov flashes caused by cosmic rays are seen to be uniformly distributed over the sky; wherever they originate in space, the charged particles are thoroughly deflected by interstellar magnetic fields. But gamma rays, unaffected by magnetic forces, travel straight from the source. Therefore, they eventually show up as a discernible enhancement, an excess signal arriving from a particular direction, over and above the smooth cosmic-ray background. (The typical resolution of a Cherenkov detector is roughly one degree—twice the moon's width as seen from the earth.)

Grindlay, determined to find a faster means of distinguishing between gamma rays and cosmic-ray particles, discovered that the sheet of Cherenkov light set off by a cosmic ray tends to be more tear-shaped, or elongated, than the flash initiated by a cosmic gamma ray. "I surmised," he says, "that this was due to a cosmic-ray shower being much richer in muons and other penetrating particles, including electrons, than a corresponding gamma-ray shower." Muons are heavier relatives (about 200 times the mass) of electron.

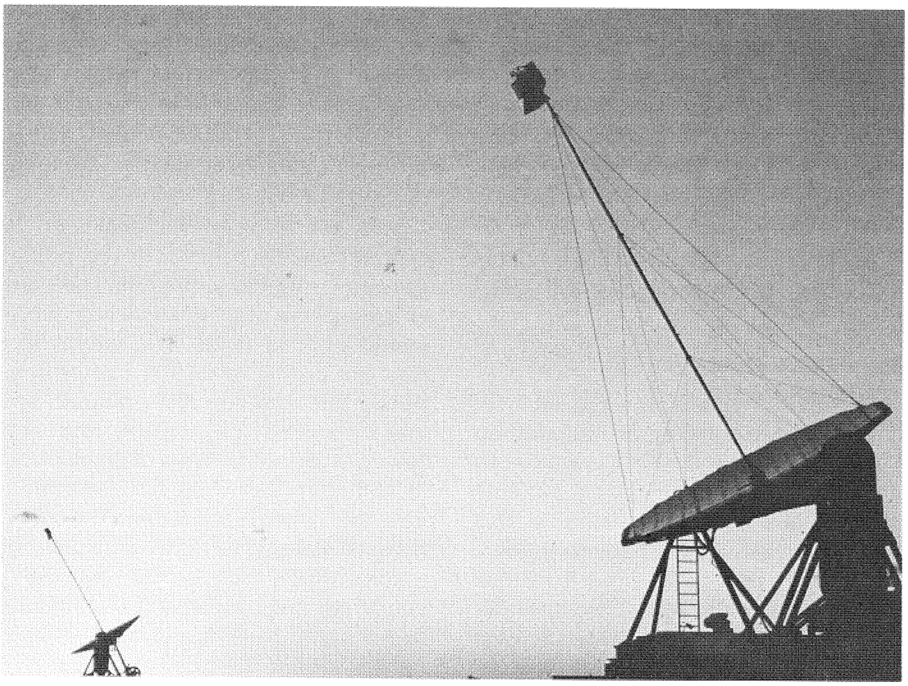
With this new means of distinguishing a cosmic ray from a gamma ray, Grindlay and his colleagues were able to detect the Crab pulsar—the compact, rapidly rotating neutron star that sits in the heart of the Crab nebula. To detect this stellar cinder, they used a series of parabolic searchlight mirrors in conjunction with the ten-meter reflector. A triangulation method using the added mirrors, set over baselines of typically 100 meters, enabled them to resolve the elongation spatially. Grindlay, utilizing a pair of large optical reflectors in Australia, went on to observe TeV astronomy's first extragalactic source—Centaurus A, which is the nearest galaxy with an active, radiation-spewing nucleus akin to a quasar.

Considering the many years put into the effort, though, the findings were rather meager. Hoping to achieve more, Fazio switched to infrared astronomy, while Grindlay entered the growing X-ray field. Yet Weekes persevered, a decision he attributes to "sheer stubbornness" as well as the opportunity to upgrade the ten-meter reflector in collaboration with researchers from Iowa State University and Ireland's University College in Dublin. Since 1983, the Whipple detector has been focusing the Cherenkov light onto an array of 37 phototubes, "which makes it the world's biggest camera," according to David Lewis of Iowa State.

Grindlay. Using the Australian telescopes (below), the one with which the first extragalactic gamma-ray source was found.

The shape and intensity of each snapshot-recorded event, a 37-pixel image received at a computer housed near the reflector, allows the astronomers to determine both the trajectory and the energy of the triggering ray. Theory suggests that a gamma ray might also be distinguished from an unwanted cosmic ray at this point by assessing the size of the Cherenkov image; the image of a gamma-ray-initiated light burst is a bit more compact. The Whipple group is working on this idea. To help them in the assessment, the number of phototubes is being increased to a hundred.

To improve their sensitivity by a factor of ten or more, the Whipple group hopes to construct at the Mount Hopkins site a second reflector, which should offer them a stereoscopic view. This $1.5 million proposal was named HERCULES (for High-Energy Radiation Cameras Using Light-Emitting Showers). In the meantime, other institutions are setting up additional VHE gamma-ray detectors in the United States. One detector, atop Mount Haleakala on the Hawaiian island of Maui, is a collaboration among the University of Hawaii,



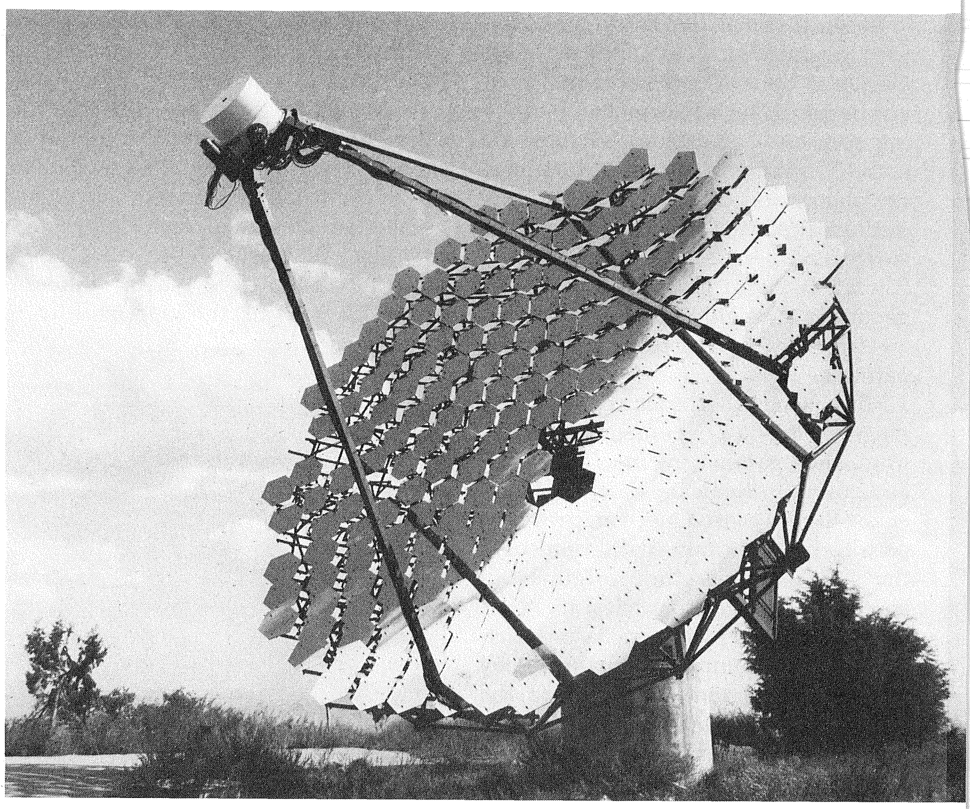
Purdue University, the University of Wisconsin, and the University of Athens. Another, at the Sandia National Laboratories in Albuquerque, New Mexico, is a joint undertaking of Sandia, the University of California at Riverside, NASA's Jet Propulsion Laboratory, and the University of Michigan. "Ultimately," says Weekes, "we would like to see a seminational facility in TeV astronomy constructed on some two-mile-high plateau, perhaps as a ring of seven 10-meter reflectors."

Other Cherenkov-light-seeking telescopes can be found around the globe: in the Soviet Union, India, Japan, and South Africa. For some years, the University of Durham, England, operated a set of four small telescopes at the Dugway Proving Ground in Utah, near an array of cosmic-ray detectors known as the "Fly's Eye." (See "Nature's Own Particle Accelerator" by M. Mitchell Waldrop, *Mosaic* Volume 11 Number 6.) Led by K. E. Turner, the British researchers moved on to Australia, to be able to survey the Southern Hemisphere better.

From this long list of participants, however, one might get a mistaken impression that the field has grown steadily since the 1960s. "Predictions of the gamma-ray fluxes from sources like the Crab turned out to be optimistic by several orders of magnitude," explains Iowa State's Richard Lamb, a member of the Whipple team who got his start in TeV astronomy in 1973 by detecting the Crab pulsar (very marginally) with an array of 32 two-foot reflectors in an Iowa cornfield. The entire field of TeV or VHE gamma-ray astronomy, in fact, nearly died of neglect in the late 1970s. "The ten-meter reflector was officially closed from 1976 until 1981," notes Weekes. His effort might never have revived (and other VHE gamma-ray systems never developed), were it not for the antics of an intriguing object called Cygnus X-3, situated at the edge of the Milky Way galaxy.

The rosetta stone

Cygnus X-3 was discovered in 1966, when an X-ray detector, carried aloft on a rocket, surveyed the Cygnus constellation. Although Cygnus X-3 is only the third-strongest X-ray source in that sector of the sky (as the name suggests), it is actually one of the most luminous objects in the Milky Way galaxy. Its radiations have to pass through an extensive amount of interstellar dust and gas before reaching the earth. Situated some 37,000 light-years away and hidden behind a dusty spiral arm, Cygnus X-3 cannot be seen at all with even the most powerful optical telescopes.



World's biggest camera. Ten-meter Whipple reflector (above) focuses light onto 37 phototubes (top right). Numbers in data display at right correspond to signal strength.

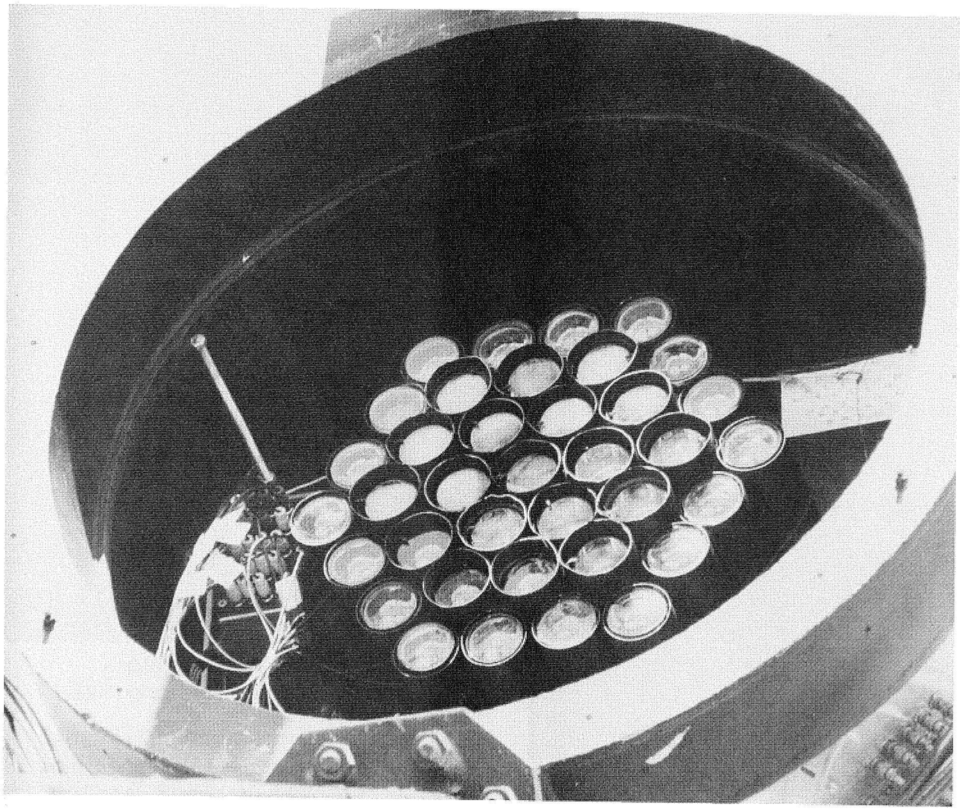
In the early 1970s the first X-ray-detecting satellite, *Uhuru*, noted that Cygnus X-3's signal waxes and wanes regularly every 4.79 hours, making it a good bet that Cygnus X-3 is a double-star system. Astronomers figure that a tiny neutron star, which is spewing the X rays, is periodically going in and out of view as it whips around a very close and more ordinary stellar companion, and that the two stars are separated by less than one million miles (roughly the diameter of the sun).

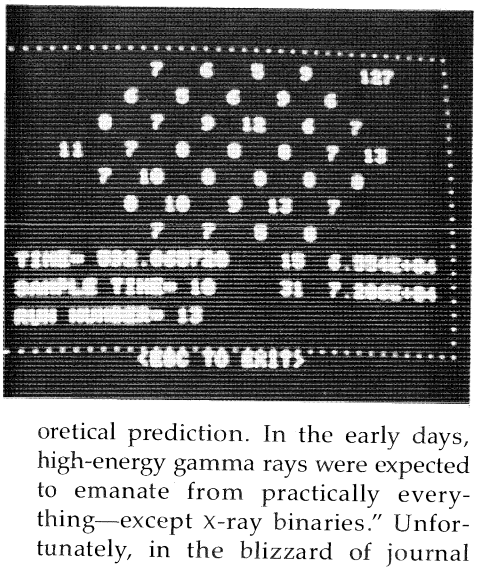
With its intense gravitational field, the compact star is believed to be pulling gas away from the companion star's outer atmosphere to wrap a swirling disk of matter around itself. The energetic X rays are produced as the matter composing this accretion disk gradually spirals in toward the neutron star, gets heated to tens of millions of degrees due to collisions between its constituent ions, and at last crashes upon the superdense surface.

For a while, Cygnus X-3 was merely one of an assortment of X-ray binaries discovered during the early days of X-ray astronomy. But in 1972, Cygnus X-3 gained a special notoriety. In September of that year, a radio astronomer in Canada, waiting for his main target to rise above the horizon, casually pointed his antenna at Cygnus X-3, already known to be a weak radio source. To his surprise, he discovered that the X-ray binary had somehow increased its radio emissions a thousandfold. For about a month, it was one of the brightest radio sources in the sky as it underwent several bursts of activity.

Astronomers around the world, alerted to the news, aimed a variety of instruments—radio, infrared, optical, X-ray, and gamma-ray—at the enigmatic object. At the Crimean Astrophysical Observatory in the Soviet Union, Arnold Stepanian and his co-workers took a look with their crude but effective Cherenkov telescope, made up of four army-surplus searchlight mirrors with phototubes at each mirror's focus. During 11 nights of observation, the Crimean instrument detected a strong flux of VHE gamma rays: Cygnus X-3 turned out to be the brightest VHE gamma-ray source on record.

"The ironic thing," Weekes comments, "is that there had been no the-





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oretical prediction. In the early days, high-energy gamma rays were expected to emanate from practically everything—except X-ray binaries." Unfortunately, in the blizzard of journal articles reporting on the bizarre behavior of Cygnus X-3, the Soviet discovery went virtually unnoticed—even when Weekes and several colleagues confirmed the Tev sighting at the Whipple Observatory in 1980. Many astronomers, wary of the air-shower data, simply did not believe it.

But they all had to pay attention when two researchers at the University of Kiel in West Germany, Wilhelm Stamm and Manfred Samorski, extended the ground-based search for gamma rays into the ultra-high-energy, or PeV, range. If a single gamma ray with an energy of 10^{14} electron volts or greater hits the atmosphere, the resulting air shower (ageometrically increasing number of electrons, positrons, and secondary gamma rays) has enough momentum to survive all the way to the ground. By then, the one-meter-thick front consists of tens of thousands of particles spread across hundreds of square meters. By detecting this cascade, with scintillation detectors set over the ground, PeV observers can calculate both the energy and trajectory of the original UHE gamma ray. The flux of PeV photons hitting the atmosphere from a typical source is about one photon per square meter per 300 years, a few hundredths of the output of TeV sources.

Kiel had an air-shower array in continuous operation between 1976 and 1980, for the purpose of studying particle interactions as cosmic rays slammed into the atmosphere. In 1982, sifting through five years of data from this array, Samorski and Stamm determined that there was a distinct quantity of UHE gamma rays arriving from Cygnus X-3, and with the X-ray binary's distinctive 4.79-hour periodicity.

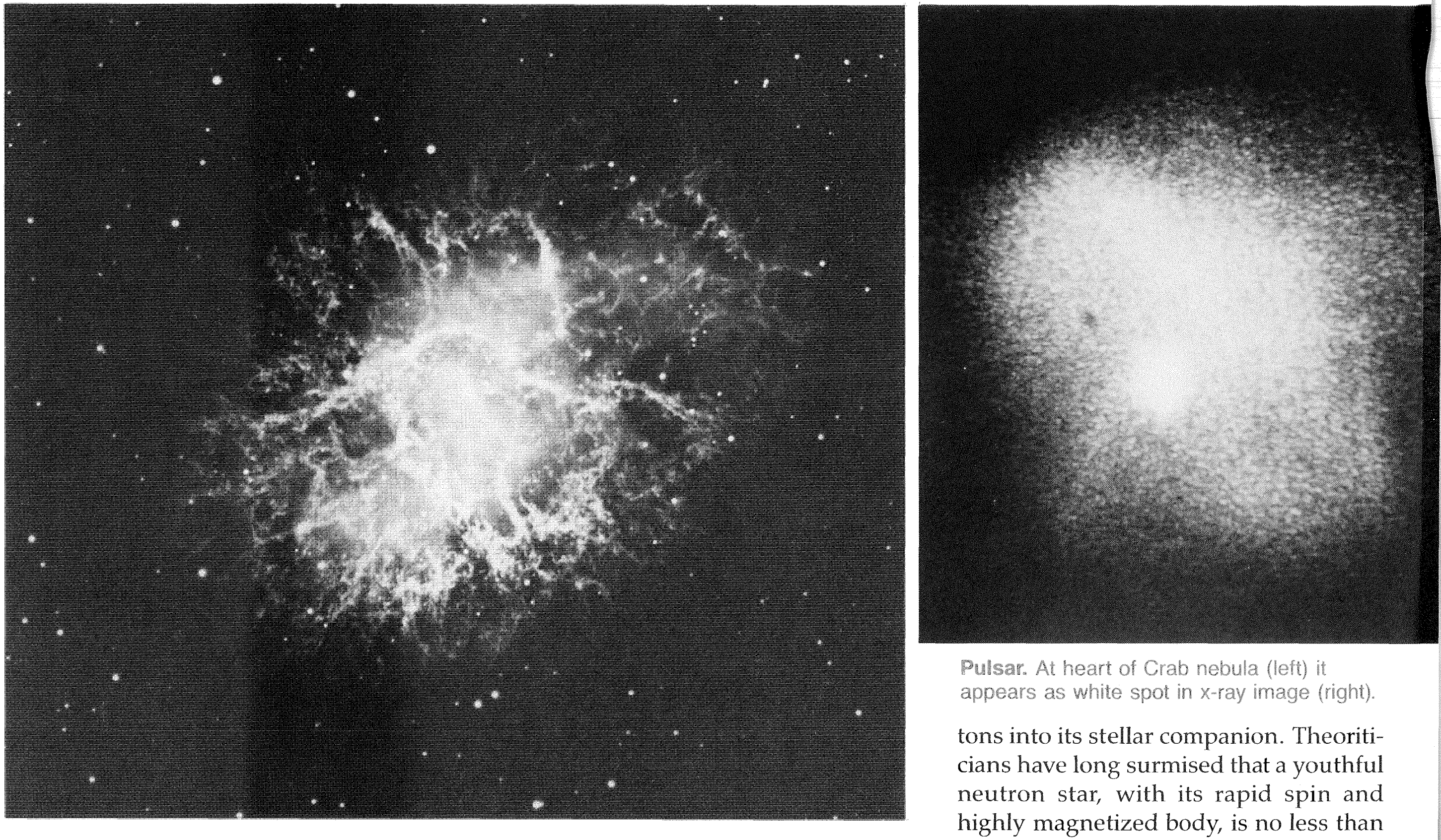
"I was skeptical at the time," recalls Jeremy Lloyd-Evans of the Los Alamos National Laboratory, who was then working at Haverah Park, the giant air-shower array that is spread for several square miles over the English moors. But his supervisor at the time, Alan Watson of the University of Leeds, encouraged him to search for the signal in Haverah Park's data. Lloyd-Evans and several Leeds colleagues soon confirmed the Cygnus find. Almost overnight, particle detectors, originally developed to observe cosmic-ray air showers, were turned into UHE gamma-ray telescopes. "The situation is unique," it was reported at a conference in 1985, "in that, even at this infant stage . . . almost every continent of the globe has at least one air-shower array [devoted to ultra-high-energy gamma-ray research]." About 16 air-shower arrays are now in operation. The emission of UHE gamma rays from Cygnus X-3 has been pretty well nailed down by groups working in the United States, India, Japan, Italy, and the Soviet Union.

Cosmic-ray source

Excitement over the discovery of the UHE gamma rays arose because of a simple, fundamental connection. "Where there are high-energy gamma rays," explains Jordan Goodman of the University of Maryland, "there are even higher-energy particles." The PeV photons were undoubtedly the products of interactions between extremely energetic particles—most likely protons—within the X-ray binary itself.

Just a few sources, like Cygnus X-3, could very well be ejecting all of the higher-energy cosmic rays that continually impinge on earth's atmosphere. Polish physicist J. Wdowczyk and his British colleague, A. W. Wolfendale, reported in the journal *Nature* that "only about thirty Cyg X-3's are needed in the Galaxy to generate the required intensity of cosmic ray particles"—a distinct possibility. It has been estimated that at any one time, there should be about 20 Cygnus-like objects residing in the galaxy. These PeV sources could be active for anywhere from 10,000 to 100,000 years. "The search for the origin of cosmic rays has been a long and conspicuously unsuccessful one," reported Alan Watson in 1985. "For the first time, a source of cosmic-ray nuclei may have been identified."

Cosmic rays, those speeding particles that permeate the entire galaxy, have long piqued the curiosity of scientists. The Austrian physicist Victor Hess first discovered the cosmic radiation during



Pulsar. At heart of Crab nebula (left) it appears as white spot in x-ray image (right).

a series of balloon flights in 1911. Some 92 percent of the particles are protons; 6 percent are helium nuclei; and one percent consists of electrons. The rest are made up of gamma rays, heavier nuclei, and other elementary particles. At various times since the particles were discovered, sources as diverse as thunderstorms and quasars have been proposed as sources of this radiation.

Several decades ago, before astronomers were aware of the universe's more violent inhabitants, the noted physicist Enrico Fermi introduced the idea that cosmic rays attain their great energies in the vast spaces between the stars. The particles are first ejected by ordinary stars as a relatively slow-moving stellar wind, he proposed, then accelerated to high velocities by means of collisions with clouds of magnetized interstellar gas or encounters with shock fronts racing away from supernova explosions. Fermi's postulated mechanism, though popular for many years, ultimately failed to explain the origin of the most energetic cosmic rays. "We knew that nucleons were accelerated to 10^{16} and 10^{17} electron volts, because we detected them with our air-shower arrays day after day after day," notes Lloyd-Evans. "But we had not a clue as to where they came from."

In recent years, it has become more fashionable to imagine discrete sources giving birth to the cosmic rays. Allegedly these objects both energize the particles and spew them out. Many candidates have been proposed, including pulsars, supernovae, active galaxies, and young, variable T Tauri stars. "Now, just one source—an X-ray binary known as Cygnus X-3—has turned out to be embarrassingly plentiful," exclaims Lloyd-Evans. In that discovery, VHE and UHE gamma rays served as the pathfinders to that source.

Theoretical models

How is Cygnus X-3 generating such a wealth of radiation? The problem of how particles are accelerated to extremely high energies is certainly taxing the imaginations of astrophysicists; the VHE and UHE gamma-ray findings have already strained theorists' models of what X-ray binaries are capable of doing. At the moment, several hypotheses are being debated.

Even before the Kiel results were published, Thomas Vestrand of the University of New Hampshire and David Eichler of the University of Maryland thought that Cygnus X-3 might be a pulsar that, as it whirls around, is periodically beaming a stream of protons into its stellar companion. Theoriticians have long surmised that a youthful neutron star, with its rapid spin and highly magnetized body, is no less than an electrical generator, which enables swarms of particles to pull away from the surface of the compact star. Guided by magnetic field lines, these radio-emitting particles are channeled into two jets that shoot out in opposite directions from the neutron star's north and south magnetic poles. The radio beams, tilted from the axis of rotation, regularly sweep across earthbound radio antennas to produce a periodic "beep" (hence, the name pulsar).

"Most people, including me, favor electrons and positrons coming from the pulsar," says Eichler, "but protons are also possible." No matter how the protons are produced, Vestrand and Eichler introduced a key point common to all models: that the gamma rays are being produced in a specific, secondary reaction.

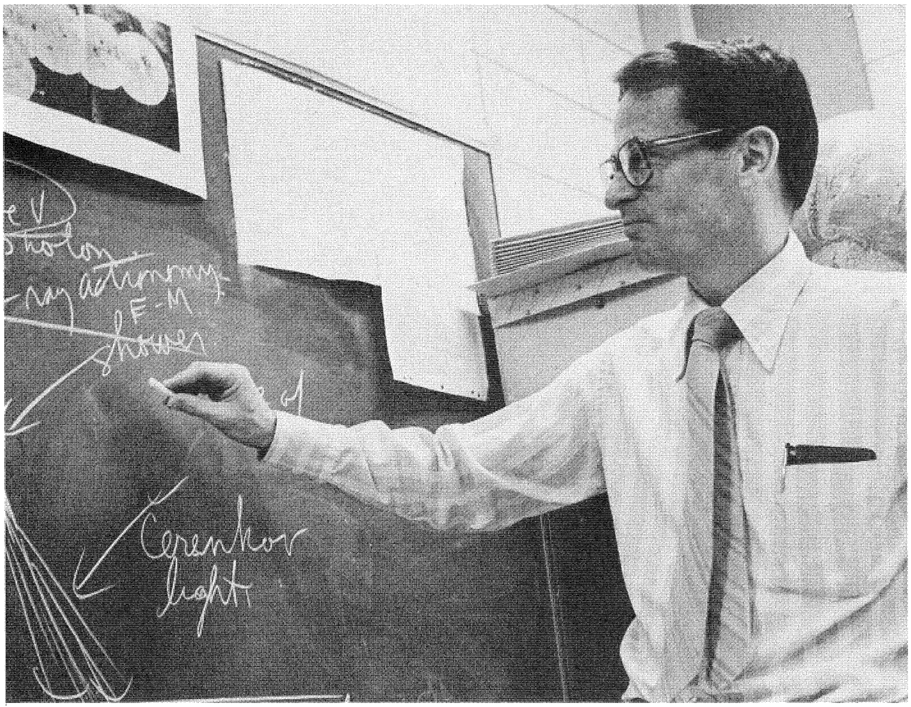
Whenever the accelerated protons strike the companion star, three kinds of particles—positively charged, negatively charged, and neutral pions—are created in the stellar envelope. The neutral pions (one-third of the total) quickly decay by emitting gamma rays. Most of this radiation will be absorbed by the massive star, but "those gamma rays just grazing the outer atmosphere of the companion, following the trajectory of the original proton, are able to get through and be detected on earth," explains Eichler. Backing up this proposition, TeV and PeV signals have sometimes peaked just at the moment when the neutron star was either coming out of eclipse or going back behind its companion star.

The pulsar model got a boost in 1985 when the Cherenkov group of the University of Durham, after observing VHE gamma-ray sources, claimed to have seen Cygnus X-3 pulsing with a period of 12.6 milliseconds, which seems to indicate that the X-ray binary contains a pulsar spinning some 80 times a second. Since the pulse is seen at no other wavelength (lower frequencies probably get attenuated by a cocoon of material around the binary), the sighting remains controversial. The Whipple team has looked and seen nothing. Weekes is cautious: "We've detected some strange things in this field that later turned out to be spurious."

"But if the pulse is confirmed," says Lloyd-Evans, "it would show that the field has come into its own." TeV astronomy would be providing information on X-ray binaries seen with no other type of telescope.

Yet the pulsar-beaming process has an Achilles heel. Since PeV astronomers are observing gamma rays from Cygnus X-3 with energies up to 10^{16} eV, the protons that produce this radiation must have been energized to 10^{17} eV or more. Current theory suggests that a pulsar simply cannot accelerate particles to such high energies. A pulsar's true capability may be only a hundredth as large.

An alternate model puts more emphasis on the accretion disk surrounding the neutron star. Ganesar Chanmugam of Louisiana State University and Kenneth Brecher of Boston University have pointed out that as the accretion disk rotates, an electric field of enormous strength is generated along the plane of the disk. That field can extend outward for nearly a million miles. "This tremendous electrical potential—some 10^{17} volts—induces a current to flow out and over the surface of the disk," explains Brecher. And as Vestrand and Eichler outlined earlier, when some of the accelerated protons collide with gas nuclei in the companion star, high-energy gamma rays are produced.



Lamb. Detected the pulsar of the heart of the Crab nebula from array in Iowa cornfield.

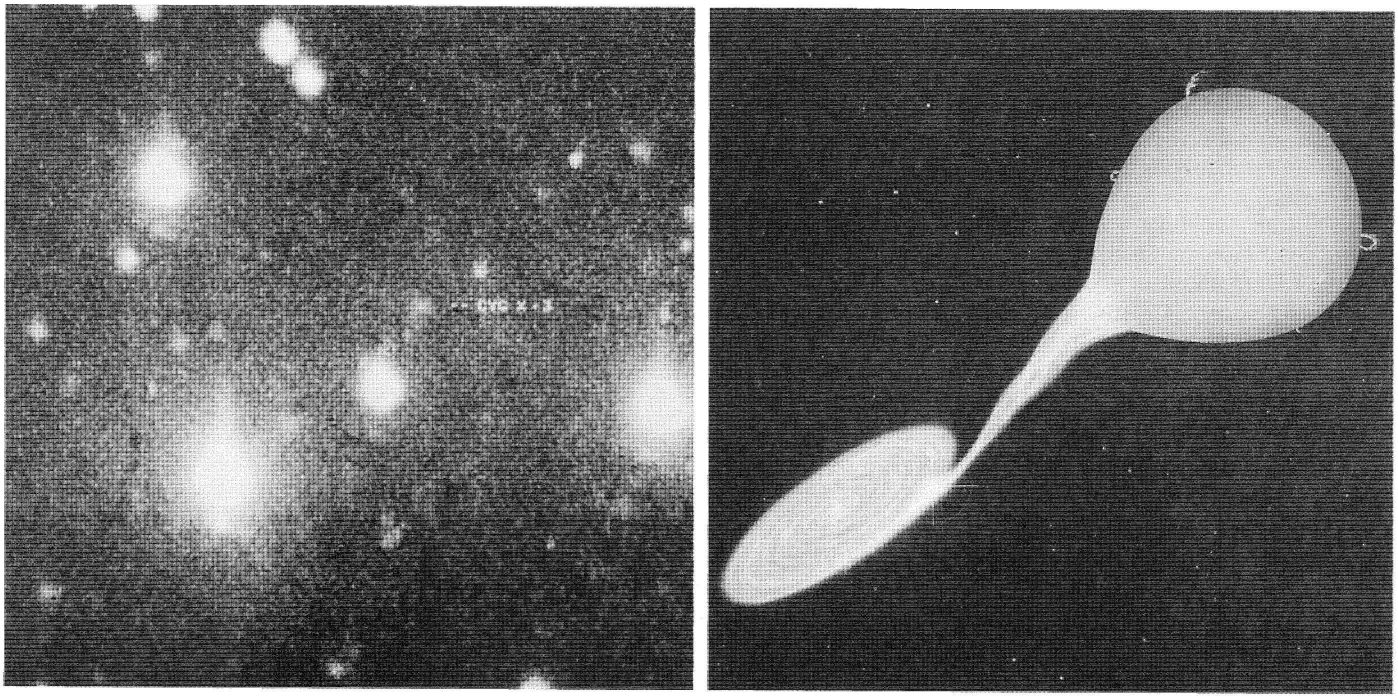
Brecher admits, though, that there is "one fly in the ointment" for the accretion model: In a stellar system chock-full of plasma, such a large electrical field would have a tendency to short out. Thus, NASA-Goddard theorist Demosthenes Kazanas is joining Eichler in beginning to consider shocks as a means of accelerating protons in X-ray binaries. A shock front would develop around the neutron star when matter, pulled off the companion star and accelerated to supersonic speeds, suddenly comes to a halt as it slams into the compact star's surface. Particles passing through such a shock zone could be energized to extremely high velocities and escape into space. Future experiments may allow astronomers to choose among the varied models. The accretion-disk hypothesis, for instance, predicts a specific flux of gamma rays that could be verified by the Gamma-Ray Observatory, a space telescope scheduled for launch into earth orbit sometime in 1990.

Whatever the mechanism, Cygnus X-3's boisterous activity is probably short lived. Theorists Floyd Stecker, Alice Harding, and John Barnard at NASA-Goddard, along with Thomas Gaisser of the Bartol Research Foundation in Delaware, have pointed out that all those charged pions—generated as the accelerated protons interact with the companion star—ultimately decay into neutrinos. The neutrinos, in turn, are probably absorbed by the companion, heating it up.

Consequently, the companion will expand. Within 10,000 years or so, it could envelop the neutron star entirely, quenching the signal. "Turning the accelerator off may not even require that the neutron star be fully engulfed," says Harding. "As the companion expands, mass transfer occurs at an increasingly higher rate. The extra matter getting dumped on the neutron star could, by itself, shut down the accelerator." Of course, if the heating ceases, the companion would contract, and the neutron star could turn on again. Thus, Cygnus X-3's exotic behavior might be periodic, perhaps over time scales as short as years. This concept could be one explanation for the infamous variability of Cygnus X-3.

Pev and Tev astronomy blossom

Cygnus X-3 was a catalyst that enabled TeV and PeV astronomers to gain more respectability within the astronomical community. "It took a long time to convince people that the subject was worthy of attention," admits Lloyd-Evans. Even many high-energy physicists are entering the field, lured by its particle-spewing discoveries. Lamb, himself a former accelerator researcher, sees high-energy gamma-ray astronomy as the means of recapturing a more personal involvement in particle physics: "Accelerator experiments these days involve hundreds of people," he observes.



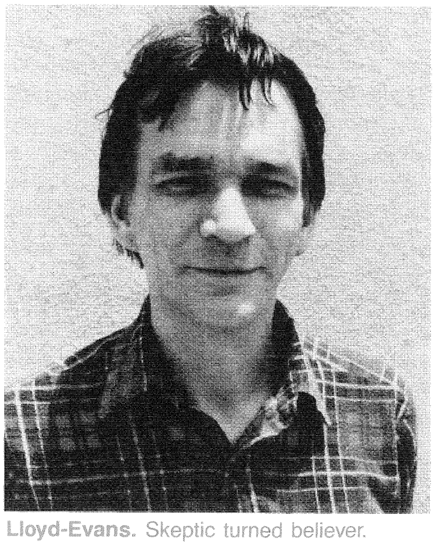
Cygnus X-3 pulsar. In near-infrared image (left) pulsar is half of a binary pair, shown in rendering (right) by Sally Bensusen.

"A hands-on participation is no longer possible."

Compared to large optical telescopes or elaborate spaceborne systems, both TeV and PeV instruments can be relatively inexpensive to assemble. Utilizing spare parts and available equipment as much as possible, researchers from the Los Alamos National Laboratory, the University of Maryland, George Mason University in Virginia, the University of New Mexico, and the University of California at Irvine were able to get an extensive PeV array—more than 60 particle detectors spread over 10,000 square meters—up and running at Los Alamos within a year and a half. Appropriately dubbed the Cygnus project, it was one of the first air-shower arrays designed solely for gamma-ray work. Someday the array may have more than 100 particle detectors.

"Los Alamos was ideally suited because it has a high altitude—nearly 7,000 feet—and a muon detector around which we could position the particle detectors," explains Maryland's Gaurang Yodh, a cosmic-ray physicist who originated the idea. In part because of the high elevation, the Los Alamos array is ten times as sensitive as the early Kiel or Haverah Park systems and can detect gamma rays down to 10^{14} ev. The muon detector, a 3.3-meter-high cube shielded by steel and concrete, is part of the Los Alamos Medium Energy Physics Facility (a pion accelerator known simply as LAMPF) that provides an added means of distinguishing between the muon-poor air showers generated by gamma rays and the muon-rich cascades originated by cosmic rays.

Each detector in the Los Alamos array is essentially a counter. The bottom, a one-meter-round slab of scintillating plastic (recycled from a 1950s MIT experiment), emits a bit of light whenever a speeding elementary particle hits it; the light, in turn, is collected by a photomultiplier tube at the top of the instrument. The response from each and every detector is relayed, via cable, to a central data acquisition and processing system.

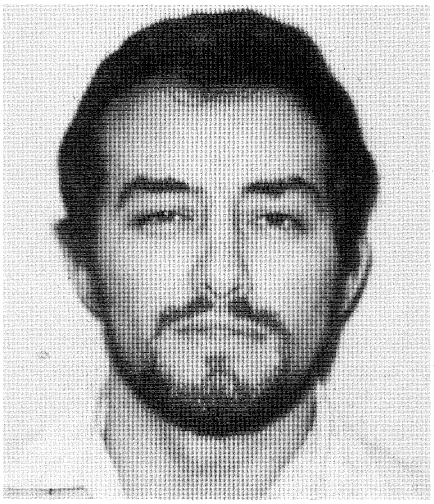


Lloyd-Evans. Skeptic turned believer.

Encased in white fiberglass cones, the detectors collectively resemble chess pawns. They are positioned about the LAMPF site, some on the accelerator's rooftop and others on the sloping grounds of the mile-high plateau, like some Brobdingnagian chess game. Darragh Nagle, a designer of LAMPF who now works on the Cygnus experiment, prefers to call the detectors schmoos, because of their resemblance to a bulbous creature in the old Li'l Abner comic strip. (Others think they resemble the tips of missiles. Indeed, the U.S. State Department reportedly received a diplomatic query when a PeV array was under construction elsewhere.)

Unlike Cherenkov telescopes, which work best on clear, moonless nights, PeV arrays can operate 24 hours a day. The Los Alamos group currently fills up a reel of computer tape each day. "An entire shower front, ten thousand or more particles, passes by within nanoseconds," says Jordan Goodman. "And," adds his Maryland colleague Brenda Dingus, "this happens dozens of times a minute." Astronomers determine the direction from which the original gamma or cosmic ray came by carefully monitoring the exact time the shower front arrives at each detector. In this way, they can establish the direction with a resolution of about 0.7 degree.

A few million events, occurring during several months, must first be recorded before a gamma-ray source can be discerned with assurance amidst the



Eichler. Favors electrons and positrons.

fierce background of cosmic rays. (Although this wait appears lengthy, smaller air-shower arrays have had to collect data for years.) Even then, Cygnus X-3 would be missed entirely were it not for its unique 4.8-hour periodicity. "There are probably 10,000 stars in that one-degree segment of sky," Goodman estimates. "We wouldn't be able to say that the gamma rays are definitely coming from Cygnus X-3, except that the signal blinks on and off at Cygnus's well-known orbital period."

Other sources

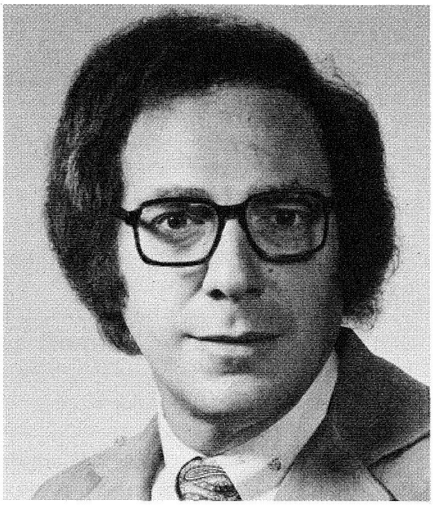
Cygnus X-3 is not the only object of interest. Shortly after Cygnus X-3 was spotted in the data from Kiel and Haverah Park, PeV gamma-ray observers around the world proceeded to search for similar signals from other X-ray binaries, the field's premier sources. The Fly's Eye, when it was used as a UHE gamma-ray telescope, detected Hercules X-1, as well as the Crab nebula. Several sources in the Southern Hemisphere, including Vela X-1, Centaurus X-3, and LMC X-4 (an object outside our galaxy in the Large Magellanic Cloud), were observed by air-shower arrays in Australia and Bolivia.

Unfortunately, several of these PeV observations have not been corroborated. Notorious for being highly variable in their gamma-ray outputs, X-ray binaries emit a kind of "now-you-see-me-now-you-don't" type of signal. Uncertainty will assuredly diminish as soon as larger air-shower arrays are constructed in the future.

Samorski and Stamm, the founding fathers of UHE gamma-ray astronomy, are setting up a 56-detector array on the Canary island of La Palma. They call it HEGRA (for High Energy Gamma Ray Array). And physicists from the Universities of Michigan, Utah, and Chicago, including Nobel laureate James Cronin, have proposed that a $3 million superarray be built at the Fly's Eye. As they conceive it, their system would spread out 1,064 scintillation stations in a gridlike pattern over 100,000 square meters—ten times the coverage of the Los Alamos array. "To do the physics properly," contends Cronin, "we have to have an array of this size." A series of muon counters, this time buried underground, would discriminate between cosmic rays and gamma rays.

Meanwhile, TeV astronomy has blossomed in light of the new evidence concerning Cygnus X-3 and its relatives. By looking at luminous X-ray binaries or lone pulsars with known periods, astronomers can verify a TeV signal much more quickly, sometimes in just one night if the intensity of the source (always highly variable) is well above the threshold of detectability. Along with Cygnus X-3, Centaurus A, and the Crab nebula and its pulsar, other well-established TeV sources now include the X-ray binaries Hercules X-1, Vela X-1, and 4U0115+63, as well as the Vela pulsar. "We still count our sources on our hands, though," jokes Lamb. "We haven't extended the count to our feet."

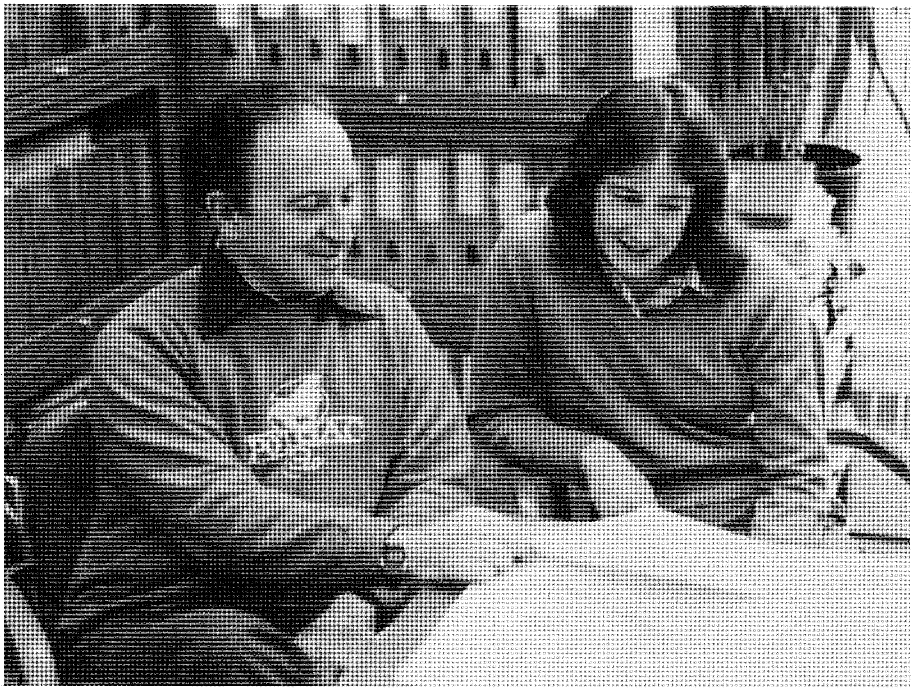
Yet even with few sources, TeV astronomers are already noticing that X-ray binaries can vary appreciably. While observing the binary system Hercules X-1, the Whipple group detected its strongest TeV signals when the neutron star in that system was completely behind its companion, the star HZ Herculis. Peter Gorham of Caltech has suggested that in this case the companion's magnetic field might be causing the protons, spewed by the neutron star, to be deflected around the companion.



Brecher. More emphasis on accretion disk.

More than gamma rays?

Fervent interest in Cygnus X-3, it should be noted, was not kindled solely by the X-ray binary's intense gamma-ray output. More tantalizing was the prospect that Cygnus X-3 might be exhibit-

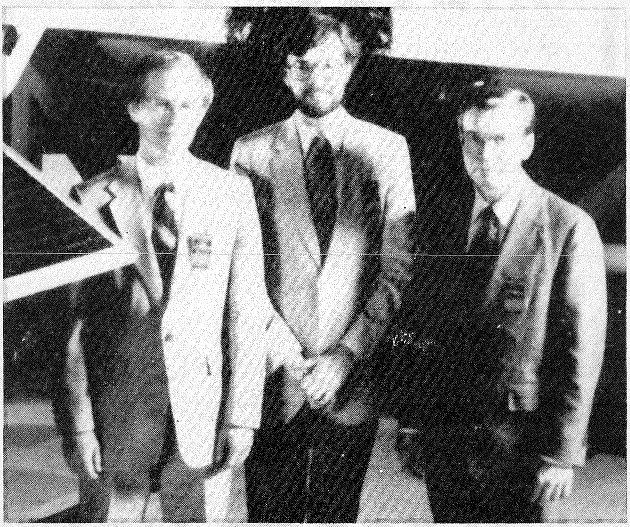


Stecker (left) **and Harding.** Cygnus X-3's boisterous activity is probably short-lived.

The lower end of the gamma-ray street

"There is no field that stimulates theorists more than gamma-ray astronomy," says Carl Fichtel, head of the gamma-ray astrophysics branch at NASA's Goddard Space Flight Center in Maryland. This is because celestial gamma rays can provide unique perspectives on the events occurring in the universe.

The dividing line between X rays and gamma rays is roughly drawn at the electron/positron annihilation line (511,000 electron volts or 0.511 Mev). Gamma rays in the low and medium bands, a range extending from about 0.1 Mev to 10 Mev, can be produced by the decay of radioactive nuclei in such sites as supernova explosions or by electrons interacting with photons and magnetic fields. The high-energy range, 10 Mev to 100 Gev (one Gev is one billion electron volts), predominantly involves nuclear interactions; these energies are often released when particles slam into one another. When it includes the very-high-energy and ultra-high-energy bands, the gamma-ray region occupies more than ten decades (a jump by a power of 10) of energy. This span of frequencies, or energies, is larger than the rest of the electromagnetic spectrum regularly viewed by astronomers.



Anticipating a 1990 launch. NASA's Don Kniffen (left), EGRET engineer Bob Ross, and Carl Fichtel.

In the 1960s, after physicist Philip Morrison alerted astronomers to the importance of gamma-ray observations, spark-chamber detectors were flown aboard high-altitude balloons. But instruments sent into orbit on satellites, far removed from atmospheric interferences, offered astronomers their first good look at the gamma-ray sky. The pioneering SAS-2 satellite conducted a seven-month mission for NASA in 1972-73; its findings were augmented by data from the European COS-B satellite, which was in operation from 1975 to 1982.

What these and other satellites unveiled was a broad region of gamma-ray emission concentrated along the plane of the Milky Way. Dotting this landscape are numerous compact sources, including the Crab and Vela pulsars, the Cygnus region, the galactic center, and several molecular-cloud complexes. More intriguing are the so-called UGOs, unidentified gamma-ray objects that cannot be associated with any known source. By some means, UGOs emit gamma rays in preference to all other forms of electromagnetic radiation.

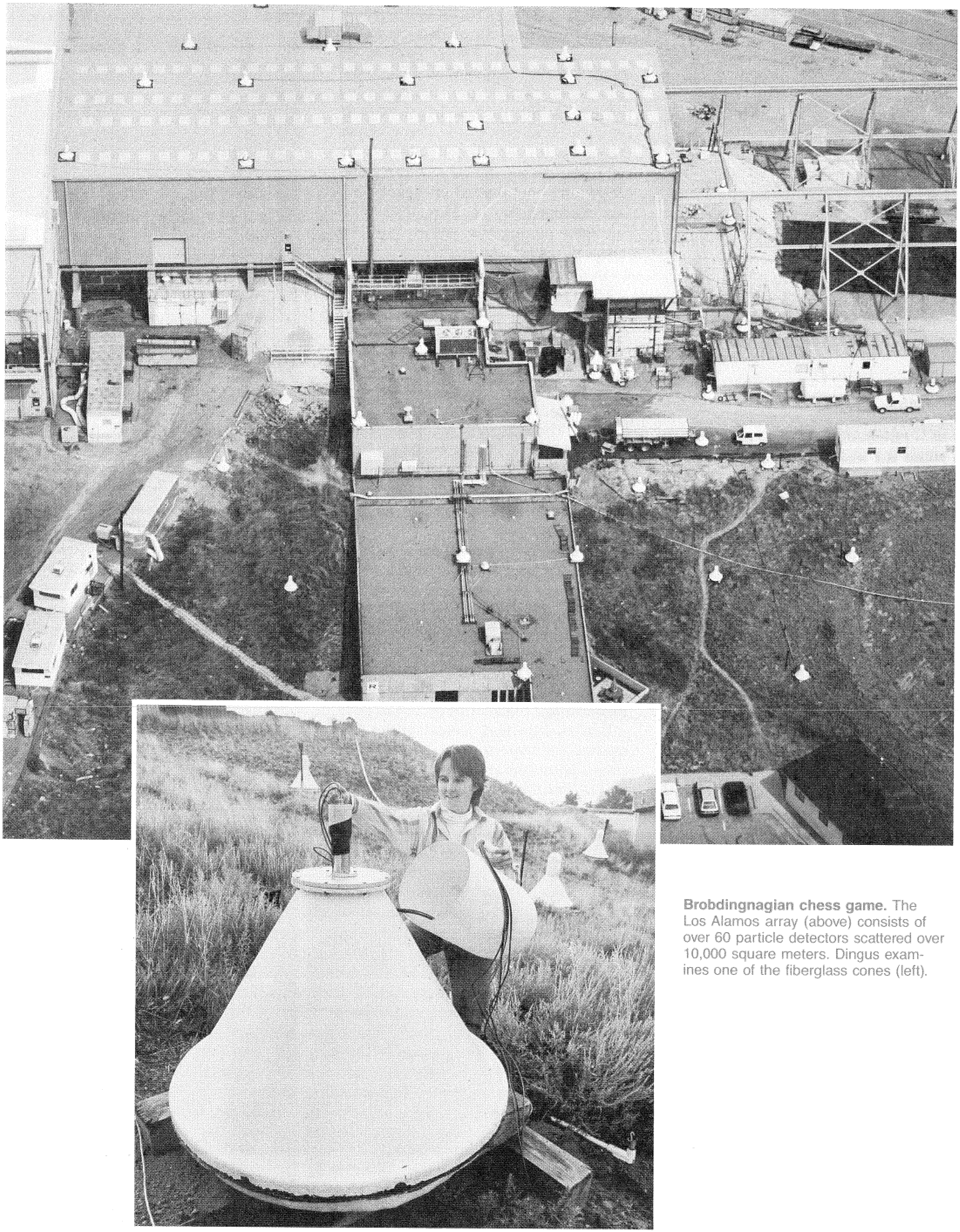
Gamma rays, with their great energies, suffer minimal absorption or scattering in space. Hence, they can reach our solar system from any part of the galaxy or cosmos. Astronomers expect that continued study of cosmic gamma-ray emission will offer unique insights on a variety of processes: the formation of the elements; the nature of the galaxy's most energetic objects, such as black holes and pulsars; the structure of the galaxy; and very early conditions in the universe.

A milestone in this endeavor is the planned 1990 launch of NASA's Gamma-Ray Observatory, a 37,000-pound, four-instrument platform that will orbit some 400 kilometers above the earth. "Gamma-ray astronomy has essentially been in a discovery phase, much like the early days of radio astronomy," points out Don Kniffen, GRO project scientist at the NASA Goddard Space Flight Center. But GRO will swiftly move gamma-ray astronomers into the next important phase: the completion of a comprehensive, all-sky survey.

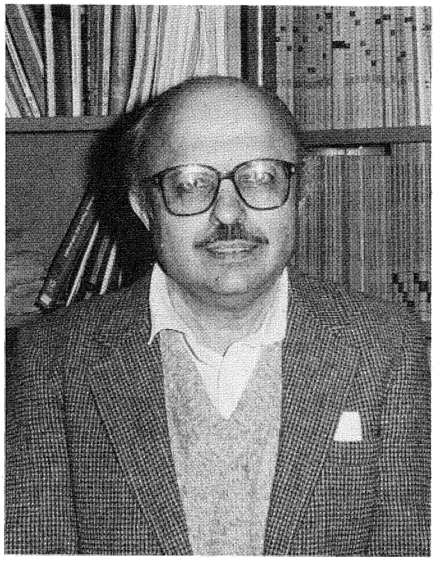
"For the first time," says Kniffen, "we'll have simultaneous observations over a full dynamic range, from tens of keV to 30 GeV," and with appreciable improvements beyond previous spaceborne detectors in their sensitivity and resolution. Along with the Energetic Gamma Ray Experiment Telescope, which will cover the high end of the spectrum, other instruments will scan the lower-energy range and be on the lookout for short-duration phenomena, such as gamma-ray bursts.

Even though celestial gamma rays are relatively rare as compared to radio or optical photons (COS-B collected only 200,000 gamma-ray photons during its nearly seven years in orbit), they pack quite a wallop. Quasars can emit as much energy in gamma rays as in any other region of the electromagnetic spectrum. "Many theoretical problems concerning active galaxies should be resolved with GRO," predicts Fichtel. "Gamma rays can tell us what is occurring in the vicinity of a supermassive black hole, which is currently presumed to be at the heart of an active galaxy."

The GRO may also help astronomers untangle the mystery of the diffuse gamma-ray background, a uniform sea of gamma rays that permeates the entire universe. Is it the collective "hum" of billions of faraway quasars, or is it the radiative glow of innumerable annihilations occurring at the boundaries between matter and antimatter superclusters (as postulated by NASA theorist Floyd Stecker)? Says Fichtel, "With GRO, we're at last going to get enough information on the kinds, numbers, and characteristics of gamma-ray objects that theorists will be able to do more than just speculate." ●



Brobdingnagian chess game. The Los Alamos array (above) consists of over 60 particle detectors scattered over 10,000 square meters. Dingus examines one of the fiberglass cones (left).



Yodh. Originated idea for Los Alamos array.

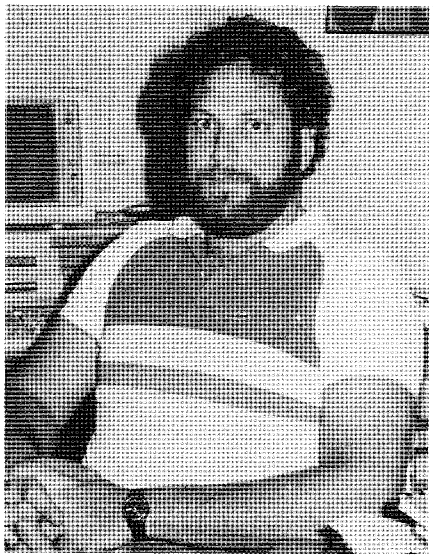
ing a whole new physics. As soon as Samorski and Stamm reported on the behavior of Cygnus X-3 in the Pev range, a nagging question arose: Was Cygnus X-3 sending more than electromagnetic radiation directly toward earth? Muon detectors operating at Kiel indicated that the air showers emanating from the direction of Cygnus tended to be rich, not poor, in muons. "This result," says Goodman, "really shook people up." Unless it turns out that gamma rays can somehow produce a lot of muons after all (which would upset what is known of nuclear interactions), the finding at Kiel suggests that something other than gamma rays—perhaps exotic particles shot out by Cygnus—was hitting earth's atmosphere. If so, to retain Cygnus X-3's distinctive 4.8-hour modulation these particles had to be capable of traveling at near-light speeds.

Unfortunately, no known particle can do the job. Buffeted by interstellar magnetic fields, charged particles could not possibly maintain a straight course from Cygnus. Neutrons would decay before they got here. Neutrinos, which can fly right through the earth, would register all the time, not just when Cygnus X-3 was overhead. So for lack of a viable candidate among the known building blocks of matter, the hypothetical particles were soon referred to as "Cygnets."

The controversy heated up in the mid-1980s, when a few groups with instruments placed deep underground studying the decay of the proton announced that their detectors were also recording intermittent showers of muons from the general direction of Cygnus. These signals, according to the reports, bore the characteristic 4.8-hour periodicity. Yet soon after, the issue became muddled: other proton-decay groups disclosed that they saw no such effect in their data.

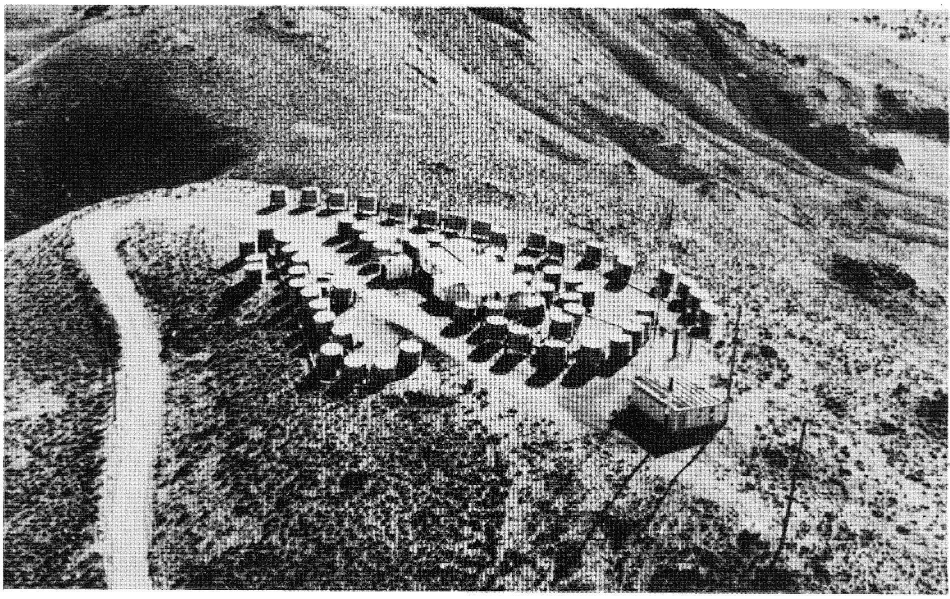
The large Los Alamos air-shower array, centered around a sensitive muon detector, was developed largely to help put the muon dispute to rest. Since the array started gathering data (in March 1986), it has tended to see muon-poor showers arriving from Cygnus. "Not zero," notes Goodman, "but a lower-than-average number of muons."

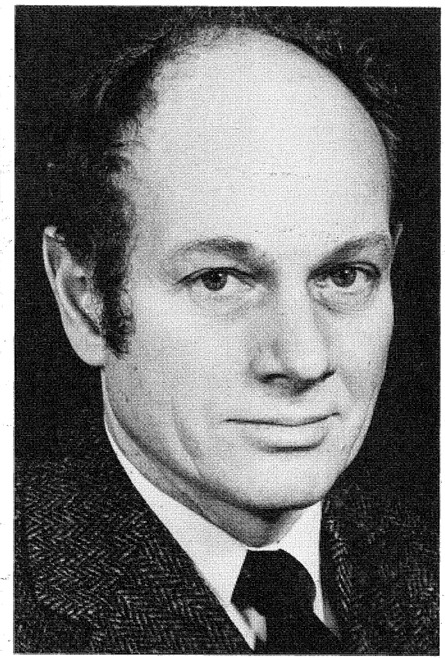
Earlier, Japanese investigators had reached the same conclusion. Because a couple of muons are seen in each event, where practically none are expected from gamma rays, some theorists are beginning to suspect that gamma rays hitting the atmosphere with energies higher than 10^{14} eV do indeed display a type of nuclear interaction not accounted for by the standard models. Physicists Gabor Domokos and Susan Kovesi-Domokos at Johns Hopkins University in Maryland have suggested that the muon surplus may be a signal that leptons and quarks, now thought to be the ultimate bits of matter, are composed of even more basic units, already being called *preons*. Since PeV signals from Cygnus X-3 barely rise above the

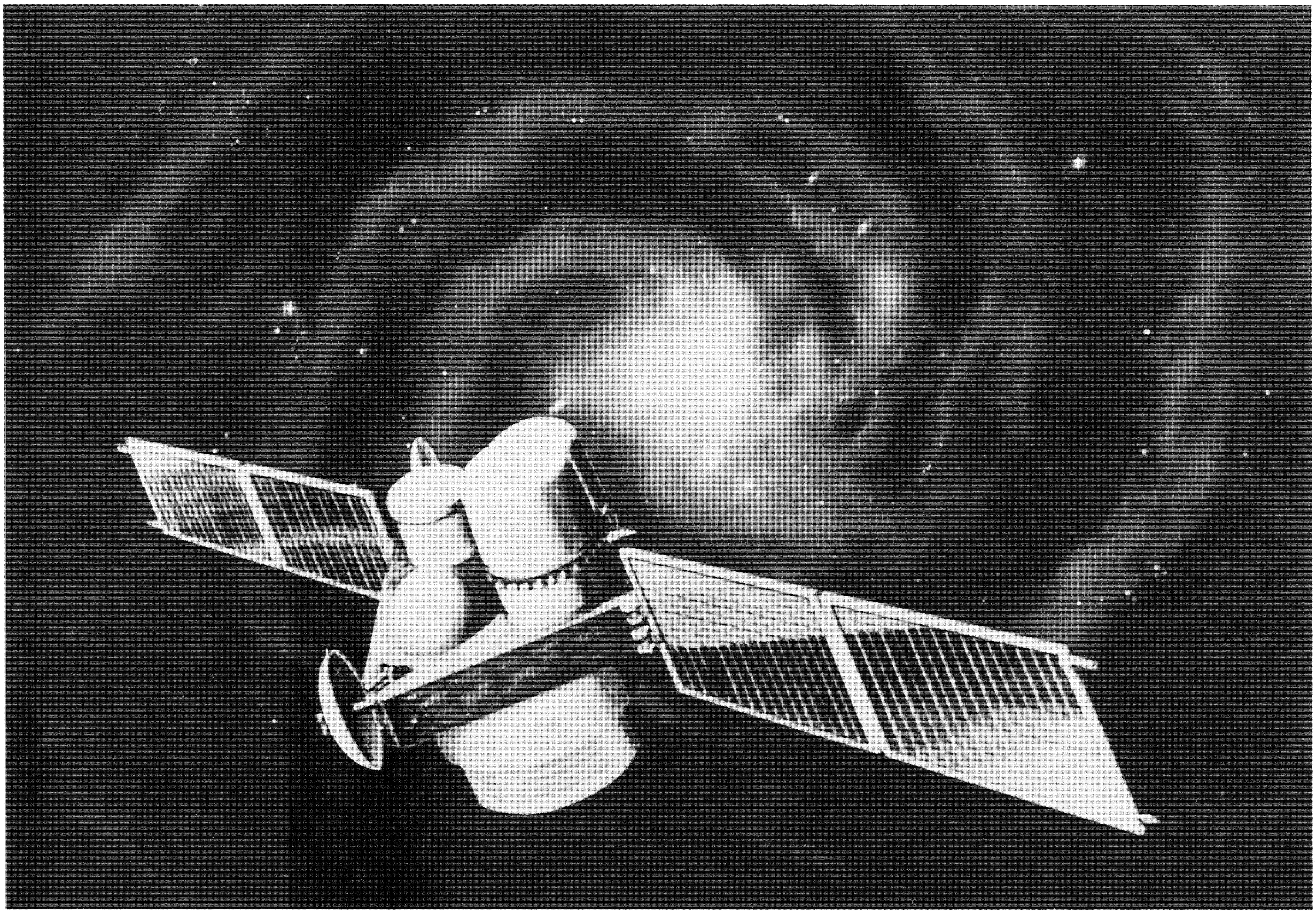


Goodman. A shower in nanoseconds.

Superarray. Fly's Eye (below left) is proposed site of superarray. Nobelist Cronin (below right) says an array this size is needed "to do the physics properly."







Sailing into the future. Artist's rendition of planned observatory for the detection of cosmic gamma-ray production.

noisy background of cosmic-ray particles, however, many more data will be needed before this matter is resolved to everyone's satisfaction.

Future plans

Both Tev and Pev astronomers are now eager to form international collaborations in order to observe their temperamental sources from different locations at the same time. "Simultaneity is a must," says Grindlay, "if the field is to get full respect." Don Kniffen, project scientist for the planned Gamma-Ray Observatory, agrees: "Every time there's a discrepancy between groups, people usually blame the source. They say it's a time variation, and that's very unsatisfactory. Simultaneous observations eliminate that excuse." To keep track of the varied sightings, Darragh Nagle would like to see a comprehensive data bank established, perhaps using a Los Alamos supercomputer.

"The most exciting development coming up," says Weekes, "will be the launch of the Gamma-Ray Observatory." In terms of energy range, the low end of the ground-based Cherenkov detectors, about 10^{11} eV, will nearly overlap with the high end of GRO's Energetic Gamma-Ray Experiment Telescope, called EGRET—one of four instruments aboard the observatory. Thus, for the first time, the ground-based systems may have the means to normalize their indirect measurements; attempts will be made to make complementary observations.

It is hoped that high-energy gamma-ray astronomy will eventually reach a level of maturity that allows observers to detect signals from undiscovered sources, objects whose pulses or orbital periods are not known ahead of time. "With enough sensitivity," says Goodman, "we might be able to look for general bumps above the background."

Nagle would not be too surprised if high-energy gamma-ray sources eventually taught builders of particle accelerators some lessons: "As one of the designers of LAMPF, I can appreciate what X-ray binaries like Cygnus X-3 are doing. Over each meter, LAMPF can accelerate a particle by one million electron volts. But Cygnus, over that distance, accelerates them by ten billion electron volts. If I could figure out how it does that," he concludes with amusement, "we wouldn't need the Superconducting Supercollider!"

Like 16th-century explorers, who often had to make several forays into unknown territory before reaping their major discoveries, researchers in both Tev and Pev astronomy are confident that their prolonged struggles will pay off handsomely in the end, enabling the two fields to stand beside their sister specialties—radio, infrared, optical, ultraviolet, and X-ray astronomy—as equals. "How many precursors to Columbus were there?" asks Richard Lamb. "In our case, we just haven't sailed far enough." ●

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