ASTROPHYSICS

Astronomers Turn New Eyes On the Cosmic Ray Sky

To understand why physicists have traditionally shunned cosmic rays, think of these mysterious visitors as gate-crashers to a party. Not only do they appear uninvited and without pedigree, but they bring with them a menagerie of other unwanted creatures whose presence can only wreak havoc. But lately, physicists have started to wonder about these mysterious strangers. Just what kind of environment could spawn this uniquely energetic lot? Cosmic rays are now in vogue.

A steady rain of these interlopers falls upon the upper atmosphere from all directions of space. As they interact with the thin gases, cascading showers of particles—billions of them—are spawned. And these, in turn, insouciantly trespass through the pristine grounds of carefully tended physics experiments, confounding detectors and ruining many a research party. But lately particle physicists have become entranced by the observation that some cosmic rays carry energies of 10^{20} electron volts (eV)—10 million times higher than will be attained by the Superconducting Super Collider (SSC). That makes them the most energetic particles in the universe, and it raises a simple question that is driving the new subfield of cosmic ray astronomy. As Nobel Prize–winning physicist James Cronin of the University of Chicago puts it: "How does nature do that?"


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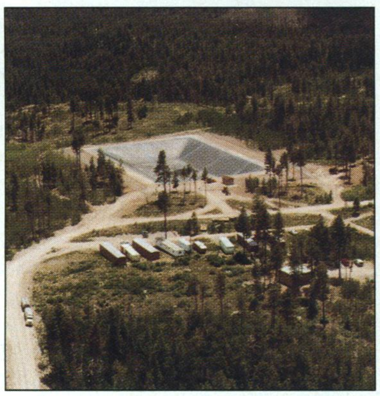
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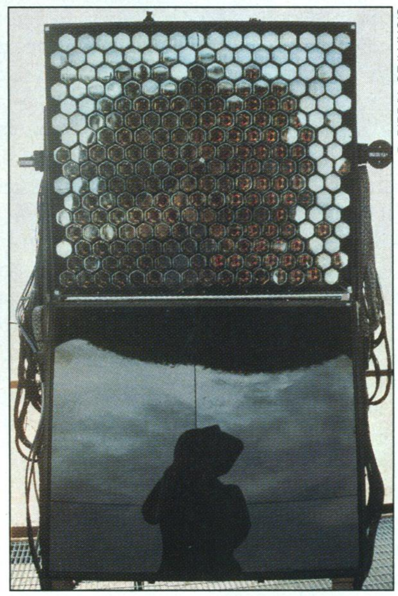
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Keen observers. Casa-Mia's array of particle detectors *(top)*, photodetectors from the prototype Fly's Eye *(right)*, and Milagro's swimming pool, which will hold layers of particle and muon detectors *(above)*.

He and other researchers are convinced that when the answer comes, it will lead to new insights about some of the most energetic domains in astrophysics: the environs of neutron stars, black holes, and active galactic nuclei. "We're talking about large-scale, incredibly energetic astrophysical processes," says Mike Salamon, a University of Utah physicist. "By understanding these cosmic rays—by measuring their composition, their energy spectrum, and arrival directions—we can learn a tremendous amount about fundamental astrophysics."

Salamon and his colleagues aren't the first generation of researchers to see potential in the cosmic interlopers, but it was only in the mid-1980s, when researchers thought they had stumbled on two potent sources of high-energy cosmic rays, the double stars Cygnus X-3 and Hercules X-1, that there seemed hope of pinning down cosmic ray origins. By now, that prospect has created a cottage industry lying at the interface of physics and astronomy. Cosmic ray detectors are up and running at Los Alamos, the Whipple Observatory in Arizona, the French Pyrenees, the Canary Islands, Japan, and Tibet. In Utah, a collaboration from the University of Chicago and the University of Michigan has inaugurated the most elaborate detector yet—a checkerboard array of 1089 sensors covering a square of desert half a kilometer on a side. Combined with the University of Utah's twin Fly's Eye detectors, it creates a facility that can detect cosmic rays in unprecedented numbers from 10^{13} eV on up to the highest energies. Still more powerful detectors, able to observe the highest-energy rays in larger numbers, are on the drawing board.

All that additional detector power is going to come in handy, because the mystery of where cosmic rays come from is now as deep as ever. The verdict on Cygnus X-3 and Hercules X-1 is in, and it's disappointing: They aren't the cosmic ray beacons they seemed to be. But that hasn't discouraged anyone, just convinced the cosmic ray crowd to settle in for a longer haul of data gathering.

The challenge amounts to reading a badly scrambled message. More than 99% of cosmic rays are charged particles—protons and heavier nuclei, from helium to lead. The galaxy's magnetic field warps these particles along curving paths so that, from Earth, they seem to emanate equally from all directions. Only neutral particles are likely to point back toward their origin, and of those, only gamma rays—high-energy photons—would survive the trip from source to Earth. (Neutrons, the most common neutral particles, would decay back into protons long before they reached Earth.) But gamma rays, says Cronin, constitute only one or two out of every 100,000 cosmic rays, which makes for a dismaying signal-to-background challenge.

Worse, at the highest energies even the "background" of charged cosmic rays dwindles to almost nothing. The flux of cosmic rays at "low" energies, explains Pierre Sokolsky of the University of Utah, is great enough that researchers can observe them directly by flying a detector in a high-altitude balloon or on a satellite. But at 10^{13} or 10^{14} eV, says Sokolsky, "you'd have to have a 10-square-meter detector in orbit for years to get just 10 or 20 events."

An undiscovered country

That energy range, however, is just where the deepest mysteries begin. The lowest energy cosmic rays—below 10^9 eV—come from the sun or, researchers believe, from the shock wave at the edge of the solar system, where particles streaming away from the sun run into the interstellar medium (*Science*, 23 October 1992, p. 549). Even up to 10^{13} eV, cosmic rays aren't a completely blank page. Observatories on the ground and in orbit have already spotted gamma rays in that energy range coming from the Crab nebula within our own galaxy and from the hearts of other "active" galaxies, such as Markerian 421, where they may be radiated by high-energy electrons accelerated in powerful magnetic fields.

Above those energies, though, begins an undiscovered country. Explains Jordan Goodman, a cosmic ray specialist at the University of Maryland, "There's a limit to how high you can accelerate electrons," because electrons readily shed their energy as synchrotron radiation—"it kills them off very quickly." The highest energy cosmic rays call for a different kind of particle accelerator—one that can fling out protons and heavy nuclei, which either survive to reach Earth or later form secondary particles and decay into gamma rays. And no one knows how such an accelerator might work or where it might be found (see box).

To snare the few cosmic rays in this energy realm, physicists use the atmosphere itself as a collector. When a cosmic ray streaks into the atmosphere, it triggers a trio of secondary effects. First comes a kind of shock wave, visible as a cone of fluorescence known as Cherenkov radiation, that points along the direction of entry, then a cascading "air shower" of a million to a billion secondary particles. Finally, atmospheric nitrogen excited by the incoming cosmic ray and the shower emits a faint fluorescence, which Ray Ong of the University of Chicago likens to "a 5-watt blue light bulb moving at the speed of light 5 kilometers away."

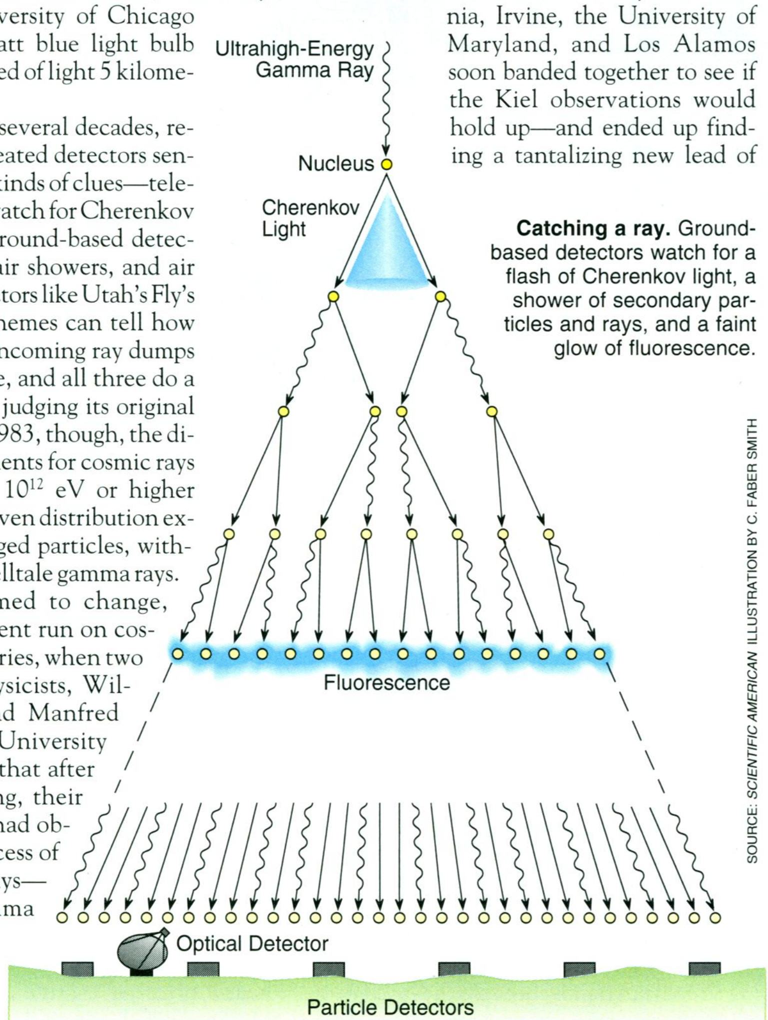
Over the past several decades, researchers have created detectors sensitive to all three kinds of clues—telescopes that keep watch for Cherenkov cones, arrays of ground-based detectors sensitive to air showers, and air fluorescence detectors like Utah's Fly's Eye. All three schemes can tell how much energy an incoming ray dumps in the atmosphere, and all three do a reasonable job of judging its original direction. Until 1983, though, the direction measurements for cosmic rays with energies of 10^{12} eV or higher showed only the even distribution expected from charged particles, without a hint of the telltale gamma rays.

All that seemed to change, sparking the present run on cosmic ray observatories, when two German astrophysicists, Wilhelm Stamm and Manfred Samorski of the University of Kiel, reported that after 4 years of running, their air shower array had observed a small excess of 10^{15} eV cosmic rays—presumably gamma rays—emanating from the direction of Cygnus X-3. In one step, the pair seemed to have solved much of the mystery of high-energy cosmic ray sources: Michael Hillas of the University of Leeds calculated that if Cygnus X-3 were producing 10^{15} eV gamma rays at the rate Kiel reported, it would have to be producing even more energetic protons at a rate so high that only five such sources would account for virtually all of the highest energy cosmic rays in the galaxy.

That was enough to excite cosmic ray specialists, but the Kiel report included something that tantalized other physicists as well. Standard physics implies that the air showers from gamma rays should include only a smattering of the electron-like particles known as muons. But Samorski and Stamm's detector had seen far more, implying either that the incoming cosmic rays were not gamma rays but some heavier neutral particle—although no other known neutral particle could have survived the journey from Cygnus X-3—or that the physics of gamma rays at these high energies was like nothing seen on Earth. Either way, the report presented the kind of paradox that physicists thrive on.

Going to the source

A collaboration of the University of California, Irvine, the University of Maryland, and Los Alamos soon banded together to see if the Kiel observations would hold up—and ended up finding a tantalizing new lead of their own. They set to work at Los Alamos to build Cygnus, an air shower array that, by covering a wider area and operating at higher altitude than the Kiel detector, would yield much better statistics. Cygnus began collecting data in March 1986. In the first year of running, the detector observed no evidence that Cygnus X-3 was generating high-energy cosmic rays. On the other hand, the data did reveal what appeared to be two distinct bursts of gamma rays at 10^{14} eV—both on July 24, 1986—from Hercules X-1, a binary star and pulsar that had been identified as a possible source of cosmic rays at lower energies.



Catching a ray. Ground-based detectors watch for a flash of Cherenkov light, a shower of secondary particles and rays, and a faint glow of fluorescence.

SOURCE: *SCIENTIFIC AMERICAN* ILLUSTRATION BY C. FABER SMITH

Meanwhile, Chicago's Cronin had also become intrigued by the Kiel report: "I said, 'Here's an experimental challenge that fits all my criteria.'" To explore it, Cronin resolved to build the biggest and most sensitive air shower array yet, able to gather as much data in 1 day as the Kiel experiment had collected in 4 years. For that, he calculated, he'd need a dense array of detectors, half a kilometer square. To help distinguish gamma rays from charged particles—and to explore the new physics promised by the Kiel observations—he hoped to couple his array with muon detectors. The Dugway Proving Grounds in Utah, where the University of Utah was already running Fly's Eye I and building Fly's Eye II, was the obvious site, says Cronin: Jack van der Velde, a high-energy physicist at the University of Michigan, was in the process of installing muon counters near Fly's Eye II to help sort out which of the cosmic rays detected by air fluorescence were gamma rays.

Funding for the $3 million project to double the number of muon counters and install the surface array didn't come easy, Cronin recalls: Ground-based gamma ray astronomy simply fell through the cracks of the funding agencies. "The astronomy division of the National Science Foundation [NSF] just couldn't conceive of this," he says, "and as for particle physics, it's a stretch of imagination saying we were doing particle physics." But NSF eventually came through, and by March 1990, the detector—known as Casa-Mia, for Chicago Air Shower Array-Michigan Array—was ready to be turned on. It then ran until April 1991 before it was put out of commission for 8 months by a lightning strike that destroyed much of the electronics. But the data gathered by then were enough to rule out Cygnus definitively as a possible point source for cosmic rays, and Hercules, as well. Says Cronin, "We've pushed the limits on the possibility of a point source of cosmic rays like Cygnus X-3 almost a factor of 100 lower than the original reports."

Sharper eyes

It's not impossible, researchers say, that Cygnus or Hercules may still emit rare bursts of cosmic rays, but they would have to do it

How Nature Might Build a Cosmic Ray Accelerator

The cosmic ray detectors expanding over the Utah desert and across the pages of grant applications are all aimed at the same question: What kind of astrophysical accelerators could spew particles and gamma rays across the universe at energies that make the planned Superconducting Super Collider look like a game of marbles? So far, researchers don't even know where to look for these cosmic ray sources—inside our galaxy or outside it. The lack of data hasn't stopped them from coming up with theoretical scenarios for a great accelerator in the sky, however, invoking such exotica as black holes, neutron stars, and the jets of material that spurt from some galaxies. But until more of the specifications are in hand, any description of a cosmic ray accelerator may be subject to change, as the latest effort goes to show.

In the 16 November 1992 *Physical Review Letters*, physicists Raymond Protheroe and A.P. Szabo of the University of Adelaide suggest that most of the cosmic rays at energies of 10^{16} electron volts (eV) —a few notches down from the very highest energies observed—come from the super-massive black holes believed to lie buried in the hearts of what are known as active galactic nuclei. The scheme seems to generate just the right number of cosmic rays to account for observations—"a remarkable numerical coincidence," according to physicist Thomas Gaisser, who has worked with Protheroe and Szabo at the Bartol Research Institute in Delaware. But it may already be running afoul of the latest experimental data.

Protheroe and Szabo's starting point is a 1986 model of how the black holes could drive the powerful emissions of radio waves and other radiation seen emanating from these active galaxies. The originators of the model, Demosthenes Kazanas and Donald Ellison of the NASA Goddard Space Flight Center in Greenbelt, Maryland, suggested that as matter falls into a black hole with a mass hundreds of millions of times that of the sun, shock waves in the inflowing current would act as powerful proton accelerators. Although the protons themselves would be trapped by the potent magnetic fields near the black hole, their energy would account for much of the galaxy's brilliance when it was transferred to other particles.

In particular, the swirling protons might collide with high-energy photons, throwing off a shower of new particles—among which, Protheroe and Szabo now suggest, would be high-energy neutrons. The neutrons, unlike the protons, would not be trapped by the magnetic fields, and could thus escape from the galactic nucleus. Being relatively short-lived, they would decay after making their escape, continuing their journey in the form of protons again. Protheroe and Szabo then calculate the number of cosmic rays their mechanism would be likely to generate in an active galaxy, multiply it by the known population of active galaxies, and come up with a cosmic ray flux at 10^{16} eV that is within an order of magnitude of what cosmic ray astronomers have observed.

Despite that success, the scenario may soon be undermined by one of its premises: that most of the cosmic rays that reach Earth at energies of 10^{16} eV or so are protons. In a paper just accepted at *Physical Review D*, physicists from the University of Utah and Bartol examine the latest data from the Fly's Eye detector in Utah, which cover an energy range around 10^{18} eV. They conclude that at those energies, protons make up only 20% of the cosmic rays—the majority are heavier nuclei. For Protheroe and Szabo's scenario to work at 10^{16} eV, says Gaisser, "there would have to be something very funny going on, a drastic change in composition between the two energies." He adds, though, that the Fly's Eye analysis is not yet iron-clad. It's just another one of the uncertainties that, Gaisser says, make tracing cosmic ray origins "a very confusing business right now."

–G.T.

when no one was looking. Casa-Mia and the Los Alamos experiment relegated Cygnus and Hercules to a minor role, at best, in the overall cosmic ray picture. So now the detector groups originally energized by the Kiel report are trying new strategies to unravel the mystery. One tack is to focus on confirmed sources of lower-energy gamma rays—the Crab nebula and Markerian 421, for example—and look for them higher in the energy spectrum. The physicists who took part in the Cygnus experiment at Los Alamos are proposing a new bilevel air shower detector, called Milagro, meant to do just that.

With one set of detectors near the surface of a pool of water, where they will observe the bulk of the particles in air showers, and another near the bottom, where only muons would penetrate, Milagro should serve as a gamma ray telescope sensitive to energies from below 10^{12} eV all the way to as high as 10^{15} eV. Says Goodman, "Within a year of turning on we should be able to see the Crab nebula very clearly at low energy. If there's something episodic going on at higher energies, this detector will be able to see it."

If efforts to track down gamma rays don't disclose a point source of cosmic rays anytime soon, a broad hint about their origin—whether they originate inside the galaxy or outside it—may come from high-energy particles like protons. If the highest energy cosmic rays do come from outside the galaxy, their abundance should show a sharp dropoff around 5×10^{19} eV. The kink is the signature of the cosmic background radiation; theory predicts that protons and heavier particles with energies of 10^{20} eV and higher should lose energy over intergalactic distances as they collide with the background radiation's photons. "Any observation of particles beyond that energy level," says Sokolsky, "tells you the universal hypothesis is not the answer." To sustain energies that high, the cosmic rays would have to originate within the galaxy.

The University of Utah's Fly's Eye detectors, which have now been collecting data on the cosmic ray spectrum above 10^{17} eV for almost a decade, may soon amass enough statistics to tell. Says Sokolsky, "We've accumulated quite a bit of data up to 10^{19} eV. Above that we can see some evidence for flattening of the spectrum, but when we get to 5×10^{19} eV we run out of statistics." To do better, Utah has begun building a prototype of a new high-resolution Fly's Eye at Dugway, in collaboration with Columbia University, the University of Illinois, and the University of Adelaide. The full-scale detector, with three instruments set 15 kilometers apart to view a larger stretch of the night sky, should improve the statistics by a factor of 10—enough to reveal the nature of the cosmic ray spectrum above 10^{19} eV. Utah is asking NSF for $15 million to build the full-scale observatory.

Jim Cronin has even bigger plans in the works. For the past year he has spent one-third of his time holding workshops and raising interest in an international collaboration that would build two air shower detectors of 5000 square kilometers each—one in the Southern Hemisphere, one in the Northern. The twin detectors would allow the physicists to scan the entire sky, while the area covered by each detector would be big enough to get meaningful statistics even at the very highest energy of the cosmic ray spectrum—10^{20} eV. Asks Cronin, "How do you get at [cosmic ray origins], other than to just replace the handful of events with hundreds and hundreds of events?" He estimates the cost at $50 million to $60 million but remarks: "That's only 10% of an SSC detector and 1% of the cost of the SSC itself." Figured as dollars per electron volt, he might add, it sounds like a bargain.

–Gary Taubes