ASTROPHYSICS

Physicists Prepare to Catch Cosmic Bullets

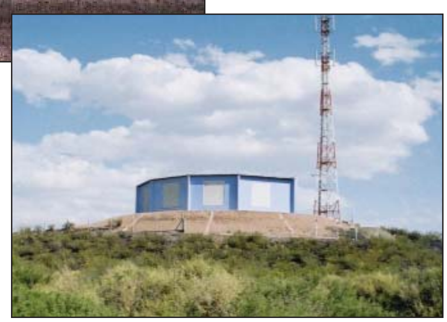
Researchers can't agree where the most energetic particles in the universe come from, or even how many of them strike Earth. An observatory under construction by physicists in 19 nations might change that

Just like any other place on Earth, the Pampa Amarilla in western Argentina is daily shot through with billions of bits of matter, cascading from the sky at just shy of the speed of light. What's different about this ancient lakebed is that soon physicists will be there ready to catch these intense sprays. In a few years, 3000 square kilometers of the desert—an area roughly the size of Rhode Island—will be scattered with 1600 detectors forming one giant observatory. The researchers who are building it, and planning a twin instrument in Utah, hope it will end decades of confusion about the origins of our highest energy visitors from outer space.

The visitors in question are particles called ultrahigh-energy cosmic rays (UHECRs). The fiercest of these travelers slam into Earth's atmosphere packing more than 100 exa–electron volts (100 EeV, or 10^{20} eV) of energy. That makes the world's most powerful particle accelerator, the 10^{12} eV Tevatron at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Illinois, look like a pea shooter. Each of these tiny subatomic particles—thought to be protons or occasionally heavier atomic nuclei such as helium and carbon—can pack as much energy as a brick dropped onto your foot or a fastball from a professional baseball pitcher.

"It's very hard to understand how to produce these particles with what we think we know about conventional physics," says Nobel laureate James Cronin of the University of Chicago. Indeed, no one knows for sure where UHECRs come from. Theories abound, from the nearby descendants of quasars to ultramagnetic neutron stars to the annihilation of clumps of superheavy dark matter. But these guesses rest on the slightest of foundations: perhaps a dozen particles above 100 EeV and a few dozen at somewhat lower energies. "It's like the early work on gamma ray bursts," comments astrophysicist Robert Streitmatter of NASA's Goddard Space Flight Center in Greenbelt, Maryland. "The number of papers is many multiples of the number of events."

That might soon change with the construction of the $54 million Pierre Auger Observatory near Malargue, Argentina, named after the French physicist who in 1938 first detected air showers from cosmic rays with detectors high in the Alps. A test array of about 30 detectors has already captured some incoming UHECRs; the full observatory should be running within 3 years. Funding permitting, Auger physicists will build an identical facility in the desert of Millard County, Utah, a few years later, enabling them to watch the sky over both hemispheres.



Desert sentinels. The Pierre Auger Observatory near the Andes will spy cosmic rays with water tanks (*above*) and fluorescence telescopes (*right*).

Cronin, the project's spokesperson, says the utter mystery of UHECRs puts the Auger team on the precipice of physics, as if perched on the snow-capped Andes above the array. "We're doing something different with our careers; it's a little off the wall, a little risky," he says. "Particle physicists will ask, 'What theory are you checking? What particle are you looking for?' I don't have the slightest idea."

Beyond the cutoff

The cosmic ray quandary is rooted in a calculation called the GZK cutoff. In 1966, American physicist Kenneth Greisen and Soviet physicists Georgi Zatsepin and Vadim Kuz'min calculated that particles above 40 EeV face draining journeys through space. Beyond that threshold, the microwaves that permeate space—the remnant heat from the big bang—appear like gamma rays to the relativistic particles. The cosmic rays collide with the faux gamma rays, losing roughly one-fifth of their energy in each encounter. The physicists figured that over a few hundred million light-years, any particle traveling faster than the GZK cutoff will have been battered down below it. So any UHECRs detected on Earth must come from nearby, usually no farther than 100 million light-years.

In light of this cosmic energy limit, physicists expected few or no events of 100 EeV or higher. Although quasars in the distant universe probably spit out such bullets, our neighborhood seemed serene. Modest arrays of particle detectors did catch a few eye-popping events (*Science*, 19 May 2000, p. 1147). But the rates were so low—barely one UHECR per square kilometer of ground per century—that researchers weren't sure whether they were flukes. "It took the community some time to accept that the ultrahigh-energy events were real," says particle physicist Glennys Farrar of New York University (NYU) in New York City.

Firmer evidence has come from two teams using different methods to spot cosmic rays. One approach uses the world's largest network of ground detectors: the Akeno Giant Air Shower Array (AGASA) near Kofu, Japan. When a cosmic ray crashes into Earth's atmosphere, it unleashes a shower of particles—muons, electrons, gamma ray photons, and others—in an expanding cone that flashes to the ground. A single UHECR can trigger an air shower involving more than 100 billion particles. AGASA spots a fraction of them with 111 detectors spread out over 100 square kilometers. A special plastic in the detectors scintillates when some of the particles zip through. With this information, the team reconstructs each event's energy using simulations of shower behavior (*Science*, 14 August 1991, p. 891). Since 1990, AGASA physicists have seen about 60 events past the GZK cutoff—and 10 events with energies above 100 EeV.

In contrast, experiments at the U.S. Army's Dugway Proving Grounds in Utah look skyward. An instrument known as Fly's Eye and its successor, High-Resolution Fly's Eye (HiRes), use segmented mirrors to monitor the air for flares of ultraviolet light—the

CREDITS: PIERRE AUGER OBSERVATORY

sign of nitrogen atoms fluorescing at the disk-shaped leading edge of the UHECR air showers. The technique works only on clear, moonless nights. However, HiRes physicists at the University of Utah in Salt Lake City and elsewhere think the technique yields a reliable, direct measure of a cosmic ray's energy. Fly's Eye and HiRes have seen only two or three events above 100 EeV in more than a decade, although the best detectors have operated for just a few years.

The gulf between AGASA and HiRes has puzzled physicists. Debates about it have spiced up recent cosmic ray conferences, including a session at an April meeting* in Albuquerque. Akeno Observatory director Masahiro Teshima said that although some adjustments in energy calculations might occur as the AGASA team refines its analysis, they won't be drastic. "We cannot change the energy scale by a factor of 2 or 3," he said at the meeting. "I'm very sure of the existence of these super-GZK particles."

However, the latest HiRes results, now in preparation for publication, strengthen the Utah team's conviction that AGASA physicists have systematically endowed their events with too much energy. "We see the GZK cutoff in action," says physicist Gordon Thomson of Rutgers University in New Brunswick, New Jersey. "Our data take a nosedive at that energy." The team also sees signs of a "pileup" of events near the 40-EeV energy level, says physicist Pierre Sokolsky of the University of Utah. That's what one would expect for particles that start out as UHECRs at great distances from Earth and then lose energy along the way. A few sources closer to our galaxy could account for the small number of extremely energetic events detected by HiRes, he notes.

The Auger Observatory might resolve the discrepancy. Physicists have combined both methods into the world's first "hybrid" cosmic ray observatory. The 1600 enclosed tanks, each containing 10,000 liters of purified water and spaced 1.5 kilometers apart, will catch air showers with energies above 1 EeV. Meanwhile, 24 fluorescence telescopes will overlook the entire array to watch for UV flashes. When the sky is clear and totally dark—about 10% of the time—the physicists will get combined data for the showers, helping them analyze each technique's systematic errors.

Engineering tests in the Argentinean pampa have already revealed one unforeseen technical challenge. "We can't leave anything that invites the resident cows to scratch themselves," says project manager Paul Mantsch of Fermilab. The physicists have had to hide all cables and make sure the tanks have no sharp edges to minimize cattle-catalyzed repairs.

* Joint meeting of the American Physical Society and the American Astronomical Society's High-Energy Astrophysics Division, 20–23 April.

CREDITS: (NIGHT SKY) CHARLES W. CAMPBELL/CORBIS; (PARTICLE SHOWER) ICRR

A zoo of sources

Once the observatory is complete, Auger physicists hope to see thousands of events above 10 EeV, some of which undoubtedly will transcend the GZK cutoff. Time will tell whether there are enough to refine theories on the possible origins of UHECRs. "Right now, I don't know of any plausible sources," says Chicago's Cronin. "That's what makes it exciting."

Ideas for how to spawn fantastically energetic cosmic rays within 100 million light-years of Earth fall into two categories. The first, dubbed "bottom-up," maintains that the particles don't start out that fast but are boosted by vast natural accelerators. Supermassive black holes in the cores of nearby galaxies could do the trick. At the Albuquerque meeting, a team led by physicist Diego Torres of Princeton University reported suggestive associations between the directions of the UHECRs detected by AGASA and four very bright nearby elliptical galaxies—possibly the remnants of quasars active billions of years ago. Black holes at their cores might spin rapidly enough to power a raging electromagnetic field of perhaps 100 billion billion volts, shooting off cosmic rays like sparks.

Image not available for online use.

Air show. The most powerful cosmic rays spark cascades of billions of particles.

However, NYU's Farrar and physicist Tsvi Piran of Hebrew University in Jerusalem suggest that relying on the incoming direction of UHECRs might be misleading. It's possible, they say, that all detected UHECRs come from the most active galactic core in the nearby universe: Centaurus A, a galaxy in the southern sky 11 million light-years from Earth. Farrar says that the paths of the particles could be bent by intergalactic magnetic fields, making them appear to come from all over the sky. This would require the magnetic fields to be stronger than now suspected.

Astrophysicist Jonathan Arons of the University of California, Berkeley, thinks we need only look inside normal galaxies, such as our Milky Way. In work he will soon submit for publication, Arons points to magnetars, unusual highly magnetized neutron stars forged by certain supernovas. A magnetar spinning thousands of times a second at birth could whip up plasmas that accelerate particles to 1000 EeV (a zetta–electron volt) or more. "This could be an interesting signature of some of the craziest supernovas you'll ever run into," Arons says. Astrophysicists Pasquale Blasi of the Arcetri Astrophysical Observatory in Florence, Italy, and Angela Olinto of the University of Chicago have also proposed this idea.

In contrast, some theorists prefer "top-down" ways of producing UHECRs, without the need for an insanely powerful accelerator. For example, the cocoon of dark matter enshrouding our galaxy might contain clumps of "superheavy" dark matter that popped into existence in the early universe. Over the millennia such clumps, dubbed "WIMPzillas" by physicist Edward Kolb of Fermilab and colleagues, would occasionally collide and annihilate each other, spewing out ferocious cosmic rays (*Science*, 19 February 1999, p. 1095). Others have proposed similar scenarios involving the decays of magnetic monopoles, cosmic strings, and other massive relics from the big bang.

"The theorists get more creative as the evidence gets more compelling," says Auger physicist James Beatty of Pennsylvania State University, University Park. "But all of the mechanisms have the problem that, in one way or another, the very existence of these particles is far-fetched."

If the Auger Observatory doesn't see enough UHECRs to unravel this knot of hypotheses, its successors might take to orbit. Both NASA and the European Space Agency (ESA) are studying proposals to scan the atmosphere for the fluorescence flashes of UHECR impacts from space. The ESA proposal, called the Extreme Universe Space Observatory, would consist of a single downward-pointing telescope on the international space station and might fly as soon as 2008. NASA is looking a few years farther down the road toward a two-satellite mission called Orbiting Wide-angle Light-collectors.

Whatever the outcome of experiments under construction or in the works, most of the bizarre notions about UHECRs will likely crash and burn. The teams wouldn't have it any other way. "Particle physics is so cut and dried with the Standard Model," says Sokolsky. "Here, it's just wild."

–ROBERT IRION

Science

Physicists Prepare to Catch Cosmic Bullets

Robert Irion

Science **296** (5576), 2134-2135.
DOI: 10.1126/science.296.5576.2134

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.