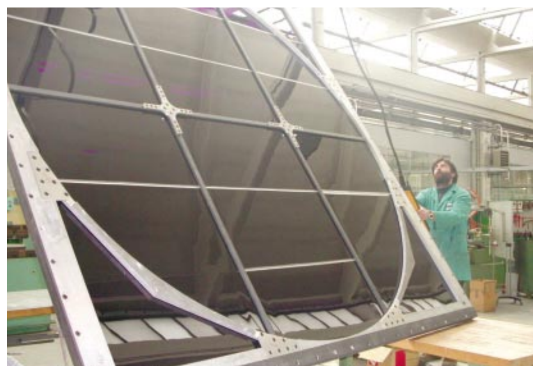
Let's catch some rays

Particles with hundreds of millions times more energy than those in physicists' accelerators regularly strike the Earth, but no one is sure where they come from. Philip Ball reports on attempts to solve the mystery.



PAO

Desert manoeuvres: using water tanks (above) and fluorescence detectors (right), researchers hope to detect ultra-high-energy cosmic rays at the Pierre Auger Observatory, currently being built in Argentina (below, left).

Argentina's Pampa Amarilla desert is filling up with water. Across thousands of square kilometres of the desert's flat plains, engineers are busy building water tanks. By 2005, 1,600 of the 11-cubic-metre tanks will be in place. But the semi-arid grasslands will not reap the benefit — the tanks are there to detect the high-energy subatomic particles that stream unseen into Earth's atmosphere.

The most energetic of these particles — called ultra-high-energy (UHE) cosmic rays — hit the Earth with about 10^{20} electron volts, or 16 joules, of energy. That's about the same as a fast-moving baseball, but carried by just a single subatomic particle. No one knows how the particles gain their energy, or why they do not lose it before arriving at Earth. Some physicists speculate that they are accelerated by shock waves from supernovae, or the slingshot action of supermassive black holes. Others invoke ideas that lie beyond the current framework of theoretical physics.

The tanks in the desert are part of the Pierre Auger Observatory (PAO), named after the French physicist who first detected cosmic rays from the ground. Most cosmic rays are protons, although a few are nuclei from elements such as helium and carbon, and some are lone electrons. In 1938, Auger showed that Geiger counters can be used to detect the shower of particles — mainly high-energy photons, electrons and muons, which are heavier cousins of the electron — created when cosmic rays collide with molecules in Earth's atmosphere.

Power shower

In the early 1960s, an array of detectors at Volcano Ranch near Albuquerque, New Mexico, first spotted UHE cosmic rays. They recorded a particle shower that seemed to originate from a cosmic ray with an energy of 10^{20} eV — much more energetic than any previously detected[1]. At first, the event was not greeted with great surprise. The flux of cosmic rays was known to decrease more or less smoothly as their energy increases: 10^{12}-eV rays fall over every square metre of Earth's surface every second, and a 10^{19}-eV particle would be expected to strike a square kilometre about once a year. Cosmic rays with energies of 10^{20} eV were not unexpected, but were thought to be very rare. "It was assumed the spectrum would just go on," says John Matthews, who studies cosmic rays at the University of Utah in Salt Lake City.

But a few years later, UHE cosmic rays suddenly became profoundly puzzling. In 1965, physicists discovered the cosmic microwave background (CMB) — a sea of photons left over from the Big Bang. Space is filled with these photons, and they interact with UHE cosmic rays. Calculations by physicists Kenneth Greisen of Cornell University in Ithaca, New York, and Georgi Zatsepin and Vadim Kuz'min of the USSR Academy of Sciences' Lebedev Institute of Physics in Moscow showed that successive collisions with CMB photons lowers the energy of a UHE cosmic ray until it drops below 6×10^{19} eV, at which point the nature of the collisions changes and no energy is lost[2,3]. It only takes a few collisions to reach this 'GZK cut-off', so how could the Volcano Ranch detectors have seen a cosmic ray above this threshold?

Experimental error has been ruled out. The Haverah Park observatory near Leeds in northern England detected UHE cosmic rays

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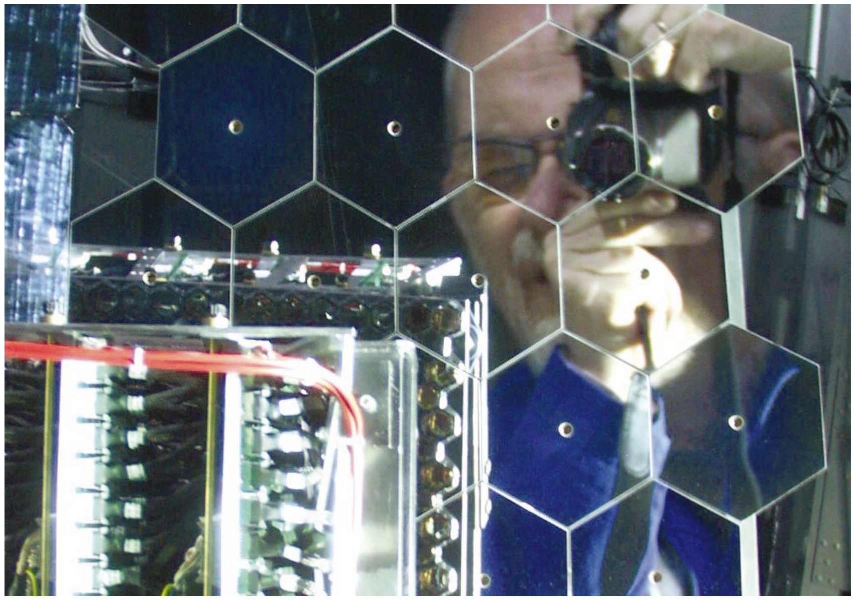


Since Pierre Auger worked out how to catch cosmic rays, many detectors, such as the Fly's Eye (right), have spotted high-energy particles.

during the 1970s, and the Akeno Giant Air Shower Array (AGASA) near Tokyo has logged 10 cosmic rays with energies above 10^{20} eV since 1993. In 1991, the Fly's Eye detector at the US Army's Dugway Proving Ground in Utah observed a massive shower of 200 billion secondary particles, apparently produced by a cosmic ray with an energy of 3×10^{20} eV (ref. 4). At five times greater than the GZK cut-off, this is the highest-energy particle ever recorded. There seems no question that these energetic particles exist, but how do they manage to reach Earth?

Violent neighbourhood

The truth must lie in the fact that the GZK cut-off is not absolute. UHE cosmic rays that are formed close enough to Earth would experience fewer collisions before reaching us, so their energies on arrival could still be above the cut-off. Physicists estimate that the source of the UHE cosmic rays must be within 200 million light years of Earth — which means that they come from nearby galaxies.

The problem is that astronomers are not sure which events are sufficiently violent and close enough to create UHE cosmic rays. "The number of sources that are close enough and are capable of producing particles of 10^{20} eV are very few," says Alan Watson, a physicist at the University of Leeds who works on the PAO team. Matthews agrees: "When we look back in the direction that the cosmic ray with 3×10^{20} eV came from, there is nothing there that looks like a potential source."

So what kind of events could generate such energetic particles? The most popular explanations are 'bottom-up' processes, in which lower-energy particles are accelerated to become UHE cosmic rays. Shock waves, perhaps generated when the expanding shell of matter from a supernova collides with the gas and dust between stars, are one possible cause, and evidence for such a mechanism has emerged in the past decade.

During the mid-1990s, the Japanese Advanced Satellite for Cosmology and Astrophysics detected X-rays from a 10,000-year-old supernova. Analysis showed that these X-rays were emitted by high-energy electrons[5]. This April, researchers working on the Japanese–Australian CANGAROO project — the Collaboration between Australia and Nippon for a Gamma Ray Observatory in the Outback — added another link between supernovae and cosmic rays. They reported that high-energy γ-rays, apparently generated by high-energy protons, seem to come from a supernova remnant in our Galaxy[6].

Both results suggest that high-energy particles of the type seen in cosmic rays are produced by supernovae. But these shock waves can only generate cosmic rays with energies up to about 10^{15} eV. Collisions between galaxies, or the jets issuing from massive black holes that are devouring stars and gas, could create bigger waves. But because there is not yet any direct evidence for either of these mechanisms, other bottom-up explanations are also being considered.

One such alternative involves supermassive black holes. If the black holes are spinning, particles drawn towards them could be pumped back out with very high energies in a kind of gravitational slingshot effect. At April's meeting of the American Physical Society in Albuquerque, New Mexico, Elihu Boldt of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and Diego Torres of Princeton University in New Jersey reported that some of the UHE cosmic rays seen by AGASA have trajectories that line up with four galaxies containing supermassive black holes, all of them within 100 million light years of Earth. Crucially, these black holes are dormant — they are no longer devouring interstellar gas and dust. If they were doing so, they would generate an abundance of photons that would collide with the UHE cosmic rays and drain their energy.

But some believe the apparent alignment could just be a coincidence. "It sounds interesting, but as yet it isn't convincing to me," says Ryoji Enomoto of the University of Tokyo, a member of the CANGAROO team. Others dispute that the alignment even exists. "We see nothing like this," says Matthews, who is involved with the successor to Fly's Eye, the High Resolution Fly's Eye. His analysis of the AGASA data indicates that the UHE cosmic rays are uniformly distributed across the sky.

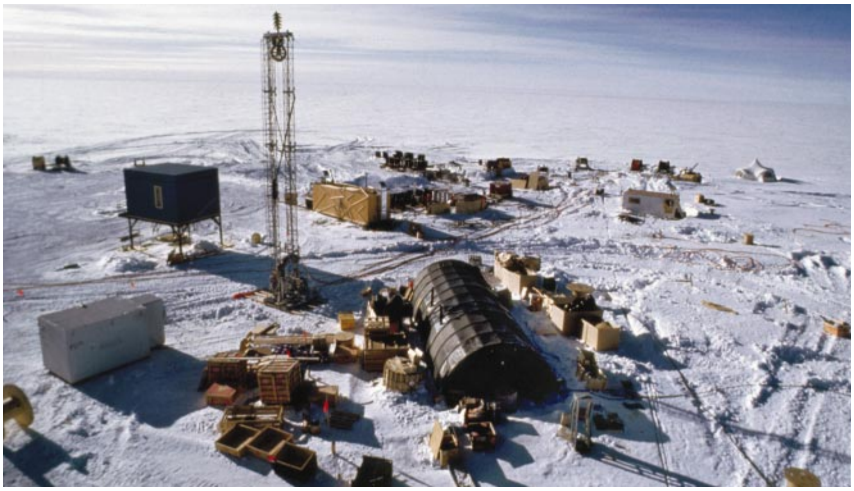
Breaking the rules

Data from the PAO and other observatories should help to settle the issue. In the meantime, more speculative theories are prospering. 'Top-down' explanations propose that UHE cosmic rays are created when even more energetic particles are slowed down. One suggestion is that the particles are produced by the decay of 'topological defects' — wrinkles in space–time left over from the Big Bang. Such defects would create an immense concentration of energy, and their decay would generate new kinds of superheavy fundamental particles, which could decay into UHE cosmic rays.

This theory lies outside of the realm of established physics, and it is not the only idea associated with UHE cosmic rays to do so. Because the rays have hundreds of millions of times more energy than particles in high-energy physicists' accelerators, their interactions could be used to study areas of physics beyond the limits of our accelerator technology. Jonathan Feng of the University of California, Irvine, and Alfred Shapere of the University of Kentucky at Lexington have proposed that cosmic rays with energies above 10^{16} eV would generate such a high concentration of energy when they collide with atoms in the atmosphere that they could create mini-black holes[7].

The standard model of particle physics says that UHE cosmic rays should not be energetic enough to do this. But this prediction would change if, as some physicists suspect,

AMANDA/ICECUBE



John Matthews says more data are needed to pinpoint the source of cosmic rays. By tracking neutrinos, AMANDA (left) may help this effort.

our Universe has more dimensions than the three of space and one of time. "Gravity is a relatively weak force in our four-dimensional world," says Feng. "But this could be because it gets diluted by spreading out in extra dimensions, unlike the other forces. If that's the case, less energetic particles can create black holes as long as they pass close enough to each other." Such black holes would decay almost instantaneously, but the shower of particles caused by this decay could be detected on the ground. If Feng and Shapere are correct, the PAO will detect around 30 showers a year from mini-black holes.

Space–time wrinkles and other extreme 'top-down' ideas elicit sceptical responses from some researchers. "I tend not to believe that the answer will be new physics," says Watson. But to test these ideas, and to compare different theories of the origin of UHE cosmic rays, researchers badly need more data on the rays that reach the Earth.

Double exposure

The PAO uses two methods to spot UHE cosmic rays, both based on detecting particle showers. Particles moving faster than the speed of light in water will emit a dim blue light, called Cerenkov radiation, as they pass through the water tanks. The particles also produce faint bursts of light when they excite nitrogen molecules in the atmosphere. This 'air fluorescence' is very dim — equivalent to a 20-watt bulb viewed from several miles away — but can be picked up on clear moonless nights by the PAO's second set of detectors: an array of sensitive photomultipliers.

By making dual detections, PAO researchers will have two independent measures of the cosmic rays' energies, allowing better calibration. "An essential feature of the PAO is the hybrid nature of the instrumentation," says Watson. "We can get signals in both detector systems 10% of the time." The data can be used to infer the trajectory of particles in a shower, and hence the path of the cosmic ray. Astronomers can then track the ray's path back and look for potential sources.

About one fortieth of the PAO's array — 40 tanks and 12 fluorescence detectors — is currently up and running. Watson says another 100 tanks and 12 fluorescence detectors should be operational in about 10 months time, and the observatory should be complete by 2005. A northern hemisphere counterpart is also planned, although no site has yet been chosen.

The search for sources of UHE cosmic rays will also soon be bolstered by data from detectors designed to spot high-energy neutrinos. The connection between neutrinos and cosmic rays is still unconfirmed, but some physicists suspect that certain astrophysical processes could produce high-energy versions of both types of particles — so tracking the neutrinos could help to pinpoint the source of UHE cosmic rays.

Neutrinos hardly interact with matter at all, but when they do, they typically produce muons that generate Cerenkov radiation. So water tanks can be used to detect neutrinos, although they have to be buried underground to shield them from the particle showers produced by cosmic rays. Several detector projects have successfully studied low-energy neutrinos over the past two decades, but building a device to snare high-energy versions is more challenging.

The neutrino trail

High-energy neutrinos are far less common than their low-energy counterparts. The two types can be distinguished by the Cerenkov trails left by the muons they create: the higher the neutrino's energy, the farther the muon travels. But high-energy neutrinos can create muon trails that are hundreds of metres long, and once the trail leaves the water tank there is no way of judging where it ends. So for researchers to be confident that they have seen a high-energy neutrino, they need to use very big volumes of water.

The solution is to abandon tanks of water and instead use the oceans or ice-caps, filtering out cosmic rays by burying the detectors deep beneath the surface. This October, European researchers in the ANTARES project will begin deploying a network of photodetectors at the bottom of the Mediterranean Sea. Around the same time, another international group will start shipping equipment to the South Pole so that the Antarctic Muon and Neutrino Detector Array (AMANDA), a high-energy neutrino detector that monitors Cerenkov trails in ice, can be upgraded. When completed in 2005, the ANTARES detector will monitor tens of millions of square metres of water. IceCube, the upgraded version of AMANDA, will cover a cubic kilometre of ice by the end of the decade.

Meanwhile, NASA has plans to send the search for UHE cosmic rays into orbit. Its orbiting wide-angle light collectors project, known as OWL, would monitor air fluorescence events from two orbiting detectors, providing a much wider search area than any ground-based detector. It will be on the look out for cosmic rays with energies in excess of 10^{19} eV, and mission scientists hope to see several hundred events per year with energies of more than 2×10^{20} eV. OWL is still in the planning phase, but researchers are aiming for a launch in 2015.

With new detector projects in the pipeline, researchers studying high-energy neutrinos and cosmic rays face a busy few years. And with such rich theories competing to explain the origin and effect of these particles, it is an exciting time. As the University of Chicago astrophysicist David Schramm, who died in a plane crash in 1997, put it: "It's an interesting field indeed where the most conservative explanations involve supermassive spinning black holes." ■

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Pierre Auger Observatory
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