

The highest-energy cosmic rays appear to come from nearby active galactic nuclei

Though it's more reassuring than surprising, this new result from the enormous Auger ground array suggests the discovery potential of cosmic-ray astronomy.

The Pierre Auger Observatory has reported its first major result. Designed to study ultrahigh-energy cosmic rays, the 3000-km² facility studs the high plains abutting the Andes in western Argentina with 1600 water-Cherenkov detectors watched over by four fluorescence telescopes (see figures 1 and 2).

Construction began in 1999 under the leadership of James Cronin (University of Chicago) and Alan Watson (University of Leeds, UK), and the Auger collaboration has been accumulating data since 2004. Now, with 1400 of the 1600 ground-array detectors in full operation, the collaboration has published evidence that the highest-energy cosmic rays appear to be coming from relatively nearby active galactic nuclei (AGNs).¹ Cronin calls it “the beginning of cosmic-ray astronomy.”

Cosmic rays with energies above 10¹⁹ eV are very attractive to astronomers. Like photons and neutrinos, they point back to their sources. Unlike photons and neutrinos, cosmic rays are charged particles—either protons or heavier nuclei. So their trajectories are bent and ordinarily scrambled by the patchy magnetic fields that pervade our galaxy and intergalactic space. But the

radius of curvature in a magnetic field is proportional to a particle's momentum. A 10¹⁹–10²⁰-eV proton is thought to be a good pointer because it would be deflected by only a few degrees in the course of a 500-million-light-year (Mly) journey through the presumed nanogauss fields of intergalactic space.

Questions and answers

Cosmic rays with energies above 6 × 10¹⁹ eV pose two intriguing questions: What mechanism could possibly accelerate individual nuclei to such enormous energies—far in excess of anything remotely conceivable with a manmade accelerator? And furthermore, how could those particles, once accelerated, maintain such energies while traversing large intergalactic distances? The two questions are related, and the new Auger result provides the clearest answer yet.

The fact that the arrival directions of those ultrahigh-energy cosmic rays show no preference for the Milky Way has long made it clear that they don't originate within our own galaxy. But in the absence of exotic new physics, there's an upper limit on how far they could have come. Above a threshold en-

ergy of 6 × 10¹⁹ eV—the so-called GZK cutoff, named after its predictors, Kenneth Greisen, Georgii Zatsepin, and Vadim Kuzmin—a proton coursing through the ubiquitous cosmic microwave background loses energy stochastically by creating pions in collisions with the low-energy photons of the CMB.

Not literally a cutoff, the GZK effect is a rather abrupt suppression at the pion-production threshold, confirmed last year by the High Resolution Fly's Eye (HiRes) fluorescence-telescope collaboration (see PHYSICS TODAY, May 2007, page 17). The suppression reflects the fact that a proton cannot remain above the threshold energy for more than about 500 Mly. Cosmologically speaking, that's still the local neighborhood. For higher arrival energies and heavier nuclei, the effective horizon is even more constricting.

Cosmic rays with energies below 10¹⁵ eV are thought to originate from supernovae and their remnant shock waves within our galaxy. But to accelerate a proton to 10¹⁹–10²⁰ eV would seem to require much larger astrophysical systems—large enough to confine the proton magnetically while it's being

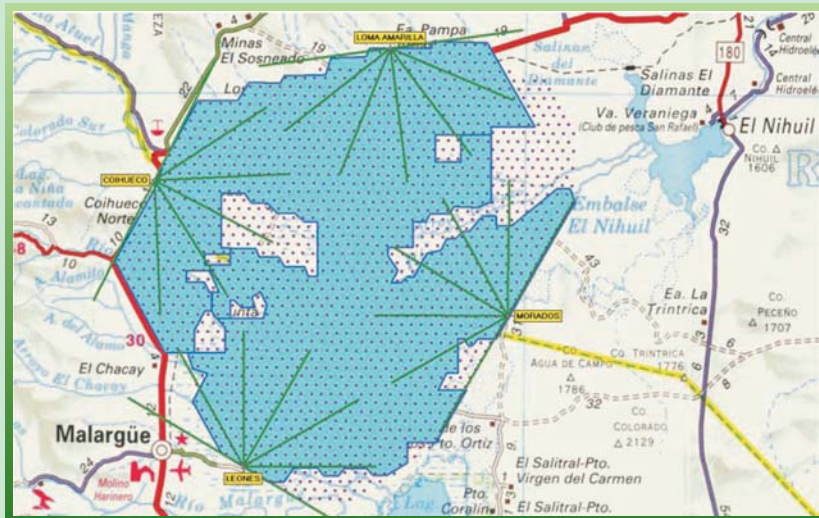


Figure 1. Covering 3000 km² of arid, high plains near the Argentinean town of Malargüe 1000 km west of Buenos Aires, the Pierre Auger Observatory has two ways of recording the extensive air showers initiated by high-energy cosmic rays: A ground array of 1600 water-Cherenkov detectors (the dots spaced 1.5 km apart) records the arrival of charged shower particles. And, on clear dark nights, four fluorescence telescopes can image the atmospheric fluorescence excited by a shower. Each telescope's field of view is suggested on the map by a fan of 20-km-long green lines. The blue area is the part of the ground array that was already in operation this past September. (Adapted from ref. 1.)

subjected to repeated shocks.

Active galactic nuclei are the prime suspects, even though it's not known in detail how an AGN would accomplish the task. Most galaxies harbor a supermassive central black hole. But an AGN differs from the relatively sedate nuclei of galaxies like our own in that its black hole is feeding so ravenously on surrounding material that the nucleus is loud at radio and x-ray frequencies and typically sports an enormous pair of jets of relativistic material.

How would one demonstrate that cosmic rays arriving at energies above the GZK threshold do indeed come from AGNs within a few hundred Mly of us? And what if that were not the case? Speculative alternatives to AGNs include young starburst galaxies undergoing prodigious star formation. And even though there's already clear evidence of the GZK suppression,² it's possible that exotic new particle physics is circumventing the suppression to some extent. For example, massive primordial particles impervious to the CMB might be decaying on our doorstep to produce ultrahigh-energy protons.

Recording showers

Unfortunately for observers, the flux of ultrahigh-energy cosmic rays is frustratingly meager. At the top of the atmosphere, one can expect about one cosmic-ray particle with energy above the GZK cutoff per square kilometer per century. That's why the Auger observatory has to cover so much ground. Although the ground array has already recorded almost a million cosmic-ray events above its effective threshold energy of about 10^{18} eV, the new paper concentrates on the few dozen of highest energy—most of them above the GZK cutoff.¹ That harvest exceeds the world total of such ultrahigh-energy cosmic rays previously reported by fluorescence telescopes and smaller ground arrays.

When a high-energy proton or nucleus (called the cosmic-ray primary) encounters the atmosphere, it initiates an extensive air shower which, by the time it reaches the ground, consists mostly of relativistic electrons, positrons, and muons. Inside each of Auger's ground-array detectors, photomultiplier tubes record the pulse of Cherenkov light generated by the passage of the shower particles through the 10 tons of water. The spacing between adjacent detectors is 1.5 km, and the shower generated by a 6×10^{19} -eV primary is wide enough to encompass a dozen of them. The microsecond differences between the arrival times of the

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Figure 2. One of the Auger ground array's 1600 water-Cherenkov detectors, with the Andes looming on the western horizon. Each detector holds 10 tons of water monitored by phototubes for Cherenkov light pulses. One can see the detector's battery pack (left), its north-facing solar panel, and its electronics dome topped by a communications mast.

shower at each of those detectors yield the incident direction of the primary to within a degree or so.

Determining the primary's incident energy is less straightforward. The more energetic the primary, the greater is the density of shower particles hitting the ground at a given distance from the shower axis. But translating shower density directly into energy has to rely on uncertain computer models of how ultrahigh-energy nuclear collisions evolve into extensive air showers.

Instead, the Auger team used hybrid events—the small fraction of cosmic-ray showers recorded by one of the fluorescence telescopes as well as by the ground array—to calibrate the ground-array density data. The telescopes, which image the fluorescent emission from excited nitrogen molecules in the air shower, function only on clear, moonless nights. But when they do see a cosmic-ray shower, they provide a rather straightforward measure of its total energy that requires no questionable computer simulation.

Seeking sources

To test the hypothesis that cosmic rays above the GZK cutoff come from local AGNs, the Auger collaboration availed itself of a catalog that gives the locations of some 700 AGNs closer than 300 Mly. To avoid the lure of statistical fluctuations that mimic true correlations, the team chose to analyze the accumulating cosmic-ray data in two sequential batches. The first, exploratory batch, comprising all events recorded through

May 2006, was used to establish cuts and tolerances for testing the hypothesis on the subsequent confirmatory batch.

Trying different cuts on the exploratory batch, the Auger team found the strongest AGN correlation signal when the minimum cosmic-ray energy was set at 5.6×10^{19} eV and source identification required that the incident direction be within 3.1° of an AGN closer to us than 240 Mly. Of the 15 events in the exploratory batch that survived the energy cut, 12 also survived the AGN source cuts; by pure chance one would have expected only 3. Those cuts were then adopted for testing the confirmatory batch (see figure 3).

Of the 13 events above 5.6×10^{19} eV in the confirmatory batch, 8 fell within 3.1° of a sufficiently local AGN. If the underlying flux were isotropic, the probability of seeing such good apparent correlation with the AGNs just by chance would be about one in 500. "So at least we've succeeded in excluding isotropy for the highest-energy cosmic rays with a confidence level of better than 99%," says Auger project manager Paul Mantsch of Fermilab.

The correlation between the cosmic-ray events and local AGNs gets even better when one takes account of unavoidable biases in the AGN catalog. Figure 3 shows an obvious dearth of cataloged local AGNs in the vicinity of our own galactic plane. That's an observational bias easily explained by the galaxy's obscuring dust. The dust would make it harder to identify AGN

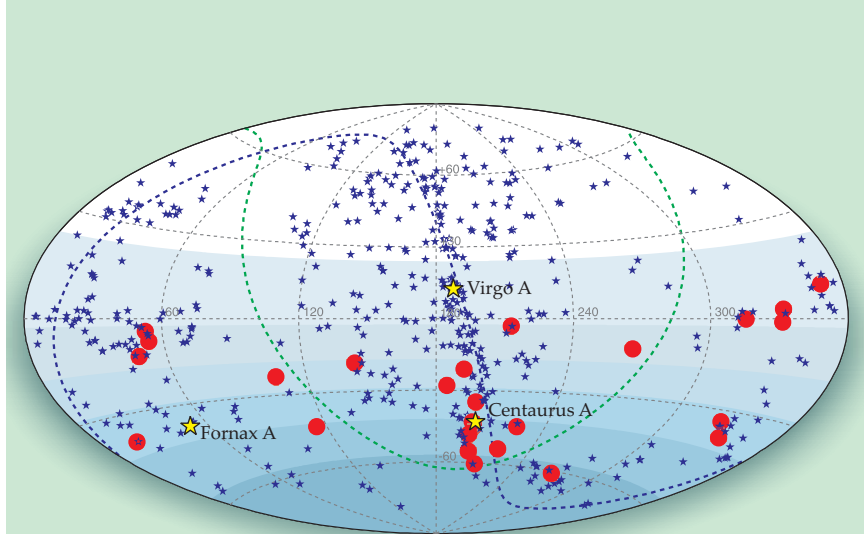


Figure 3. Arrival directions of the 27 cosmic rays with energies above 5.7×10^{19} eV recorded by the Auger ground array are indicated by red dots, each with a radius of 3.1° on this sky map in celestial coordinates. Because the observatory is in Argentina, almost all of them are below the equator. Star-shaped points mark 472 active galactic nuclei known (from their redshifts) to be closer than 240 million light-years. Yellow stars mark the three closest AGNs, from which one might ultimately expect the most events. (Centaurus A is only 8 Mly away.) The blue dashed curve indicates the supergalactic plane, along which local AGNs and other nearby galaxies cluster. The green dashed curve is the plane of our own galaxy, through which it's hard to see AGNs. The white region of northern sky is inaccessible to Auger. (Adapted from ref. 1.)

sources for cosmic rays arriving from that direction. "Indeed, if we ignore the events closest to the galactic plane," says Mantsch, "our full sample ends up with 19 events out of 21 identified with local AGNs."

What about the admixture of heavy nuclei in cosmic-ray flux? The data exhibit strong correlation for any choice of energy cut near the GZK pion-production threshold calculated explicitly for protons. Another indication that the observed correlation is due primarily to protons is its manifestation at separation angles as small as 3° . Because

bending in a magnetic field increases with charge, an incoming heavy nucleus points much less reliably to its source.

"We can't yet claim to have proven that AGNs within the GZK horizon are the actual sources," says Auger spokesman Watson. Figure 3 shows a clustering of cosmic-ray events near the supergalactic plane, a sheetlike structure that encompasses our local supercluster of galaxies as well as several neighboring superclusters. But that's where all sorts of other galaxies mingle with our local AGNs. So it might be that the sources are starburst galaxies or

other astrophysical systems in the same crowded environs.

With its full complement of ground-array detectors soon to be in operation, the Auger collaboration hopes to address these and other questions with about 30 new events above the GZK energy per year. An interesting issue, for example, is whether these cosmic rays come only from some recognizable subclass of AGNs. Ultimately observers hope that, with enough statistics, energy spectra of cosmic rays from individual sources will elucidate the mechanisms by which protons and heavy nuclei are accelerated to ultrahigh energies.

In the light of Auger's published result, the HiRes team has reexamined its ultrahigh-energy cosmic-ray data accumulated over a decade before the facility's shutdown last year. "With 13 events above the GZK cutoff," says the team's Gordon Thomson (Rutgers University), "we've found no significant correlation between their arrival directions and local AGNs."

The HiRes team and a Japanese group have joined forces to operate a new cosmic-ray observatory in Utah that combines fluorescence telescopes with a 1000-km² ground array. Called the Telescope Array Experiment, the new facility began taking data in November. The Auger collaboration is also turning its attention to the northern sky. It's seeking funds to start building a second 3000-km² observatory at a site near the town of Lamar in southeastern Colorado.

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References

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Quantum spin Hall effect shows up in a quantum well insulator, just as predicted

The effect, which occurs without a magnetic field, is a new and topologically distinct electronic state.

Five years ago, two groups of theorists made a bold proposal: If you apply a voltage to the ends of a semiconducting strip, spin-up electrons will accumulate along one edge, while spin-down electrons will accumulate along the other.

Spin segregation had already been predicted to occur when electrons scatter off impurities, an effect known as the extrinsic spin Hall effect. What made the new proposal intriguing is the mechanism: Under the right conditions, a material's intrinsic band structure, not its ex-

trinsic impurities, would sort the spins.

Whether this intrinsic spin Hall effect could be observed was controversial. Even in that paragon of purity, epitaxially grown gallium arsenide, scattering seemed likely to smother the effect (see *PHYSICS TODAY*, February 2005, page 17).

Despite the initial controversy—and perhaps because of it—the two papers set off an explosion of interest in band-based spin flow. Together, the papers have already garnered nearly 2000 citations. Shuichi Murakami and Naoto

Nagaosa of the University of Tokyo and Shou-Cheng Zhang of Stanford University wrote one of the papers.¹ The other was by Jairo Sinova of Texas A&M University, Allan MacDonald of the University of Texas at Austin, and their collaborators.²

Among the ideas the papers spawned was the possibility that the intrinsic spin Hall effect, like the classical Hall effect, has a quantum cousin. The quantum Hall effect shows up when a strong magnetic field is applied to a frigid semiconducting strip. Electrons