Study confirms 1966 prediction: The most energetic particles in the universe are not from the neighborhood

Final results from the University of Utah's High-Resolution Fly's Eye cosmic ray observatory show that the most energetic particles in the universe rarely reach Earth at full strength because they come from great distances, so most of them collide with radiation left over from the birth of the universe.

The findings are based on nine years of observations at the now-shuttered observatory on the U.S. Army's Dugway Proving Ground. They confirm a 42-year-old prediction – known as the Greisen-Zatsepin-Kuzmin (GZK) "cutoff," "limit" or "suppression" – about the behavior of ultrahigh-energy cosmic rays, which carry more energy than any other known particle.

The idea is that most – but not all – cosmic ray particles with energies above the GZK cutoff cannot reach Earth because they lose energy when they collide with "cosmic microwave background radiation," which was discovered in 1965 and is the "afterglow" of the "big bang" physicists believe formed the universe 13 billion years ago.

The journal *Physical Review Letters* published the results Friday, March 21.

The GZK limit's existence was first predicted by Kenneth Greisen of Cornell University while visiting the University of Utah in 1966, and independently by Georgiy Zatsepin and Vadim Kuzmin of Moscow's Lebedev Institute of Physics.

"It has been the goal of much of ultrahigh-energy cosmic ray physics for the past 40 years to find this cutoff or disprove it," says physics Professor Pierre Sokolsky, dean of the University of Utah College of Science and leader of the study by a collaboration of 60 scientists from seven research institutions. "For the first time in 40 years, that question is answered: there is a cutoff."

That conclusion, based on 1997-early 2006 observations at the High Resolution Fly's Eye cosmic ray observatory (nicknamed HiRes) in Utah's western desert, has been bolstered by the new Auger cosmic ray observatory in Argentina. During a cosmic ray conference in Merida, Mexico, last summer, Auger physicists outlined preliminary, unpublished results showing that the number of ultrahigh-energy cosmic rays reaching Earth drops sharply above the cutoff.

So both the HiRes and Auger findings contradict Japan's now-defunct Akeno Giant Air Shower Array (AGASA), which observed roughly 10 times more of the highest-energy cosmic rays – and thus suggested there was no GZK cutoff.

Cosmic Rays: Far Out

Last November, the Auger observatory collaboration – to which Sokolsky also belongs – published a study suggesting that the highest-energy cosmic rays come from active galactic nuclei or AGNs, or the hearts of extremely active galaxies believed to harbor supermassive black holes.

AGNs are distributed throughout the universe, so confirmation that the GZK cutoff is real suggests that if ultrahigh-energy cosmic rays are spewed out by AGNs, they primarily are very distant from the Earth – at least in Northern Hemisphere skies viewed by the HiRes observatory. University of Utah physics Professor Charlie Jui, a co-author of the new study, says that means galaxies beyond our "local" supercluster of galaxies at distances of at least 150 million light years from Earth, or roughly 870 billion billion miles. [In U.S. usage, billion billion is correct here and in subsequent references for 10 to the 18th power. In British usage, 10 to the 18th power should be million billion.]

However, unpublished results from HiRes do not find the same correlation that Auger did between ultrahigh-energy cosmic rays and active galactic nuclei. So there still is uncertainty about the true source of extremely energetic cosmic rays.

“We still don’t know where they’re coming from, but they’re coming from far away,” Sokolsky says. “Now that we know the GZK cutoff is there, we have to look at sources much farther out.”

In addition to the University of Utah, High Resolution Fly’s Eye scientists are from Los Alamos National Laboratory in New Mexico, Columbia University in New York, Rutgers University – the State University of New Jersey, Montana State University in Bozeman, the University of Tokyo and the University of New Mexico, Albuquerque.

Messengers from the Great Beyond

Cosmic rays, discovered in 1912, are subatomic particles: the nuclei of mostly hydrogen (bare protons) and helium, but also of some heavier elements such as oxygen, carbon, nitrogen or even iron. The sun and other stars emit relatively low-energy cosmic rays, while medium-energy cosmic rays come from exploding stars.

The source of ultrahigh-energy cosmic rays has been a mystery for almost a century. The recent Auger observatory results have given the edge to the popular theory they originate from active galactic nuclei. They are 100 million times more energetic than anything produced by particle smashers on Earth. The energy of one such subatomic particle has been compared with that of a lead brick dropped on a foot or a fast-pitched baseball hitting the head.

“Quite apart from arcane physics, we are talking about understanding the origin of the most energetic particles produced by the most energetic acceleration process in the universe,” Sokolsky says. “It’s a question of how much energy the universe can pack into these extraordinarily tiny particles known as cosmic rays. … How high the energy can be in principle is unknown. By the time they get to us, they have lost that energy.”

He adds: “Looking at energy processes at the very edge of what’s possible in the universe is going to tell us how well we understand nature.”

Ultrahigh-energy cosmic rays are considered to be those above about 1 billion billion electron volts (1 times 10 to the 18th power).

The most energetic cosmic ray ever found was detected over Utah in 1991 and carried an energy of 300 billion billion electron volts (3 times 10 to the 20th power). It was detected by the University of Utah’s original Fly’s Eye observatory, which was built at Dugway during 1980-1981 and improved in 1986. A better observatory was constructed during 1994-1999 and named the High Resolution Fly’s Eye.

Jui says that during its years of operation, HiRes detected only four of the highest-energy cosmic rays – those with energies above 100 billion billion electron volts. AGASA detected 11, even though it was only one-fourth as sensitive as HiRes.

The new study covers HiRes operations during 1997 through 2006, and cosmic rays above the GZK cutoff of 60 billion billion electron volts (6 times 10 to the 19th power). During that period, the observatory detected 13 such cosmic rays, compared with 43 that would be expected without the cutoff. So the detection of only 13 indicates the GZK limit is real, and that most ultrahigh-energy cosmic rays are blocked by cosmic microwave background radiation so that few reach Earth without losing energy.

The discrepancy between HiRes Fly's Eye and AGASA is thought to stem from their different methods for measuring cosmic rays.

HiRes used multifaceted (like a fly's eye) sets of mirrors and photomultiplier tubes to detect faint ultraviolet fluorescent flashes in the sky generated when incoming cosmic ray particles hit Earth's atmosphere. Sokolsky and University of Utah physicist George Cassiday won the prestigious 2008 Panofsky Prize for developing the method.

HiRes measured a cosmic ray's energy and direction more directly and reliably than AGASA, which used a grid-like array of "scintillation counters" on the ground.

The Search Goes On

University of Tokyo, University of Utah and other scientists now are using the new $17 million Telescope Array cosmic ray observatory west of Delta, Utah, which includes three sets of fluorescence detectors and 512 table-like scintillation detectors spread over 400 square miles – in other words, the two methods that produced conflicting results at HiRes and AGASA. One goal is to figure out why ground detectors gave an inflated count of the number of ultrahigh-energy cosmic rays.

The Telescope Array also will try to explain an apparent shortage in the number of cosmic rays at energies about 10 times lower than the GZK cutoff. This ankle-shaped dip in the cosmic ray spectrum is a deficit of cosmic rays at energies of about 5 billion billion electron volts.

Sokolsky says there is debate over whether the "ankle" represents cosmic rays that run out of "oomph" after being spewed by exploding stars in our galaxy, or the loss of energy predicted to occur when ultrahigh-energy cosmic rays from outside our galaxy collide with the big bang's afterglow, generating electrons and antimatter positrons.

The Telescope Array and Auger observatories will keep looking for the source of rare ultrahigh-energy cosmic rays that evade the big bang afterglow and reach Earth.

"The most reasonable assumption is they are coming from a class of active galactic nuclei called blazars," Sokolsky says.

Such a galaxy center is suspected to harbor a supermassive black hole with the mass of a billion or so suns. As matter is sucked into the black hole, nearby matter is spewed outward in the form of a beam-like jet. When such a jet is pointed at Earth, the galaxy is known as a blazar.

"It's like looking down the barrel of a gun," Sokolsky says. "Those guys are the most likely candidates for the source of ultrahigh-energy cosmic rays."

Source: University of Utah