COSMIC BACKGROUND BY MARCIA BARTUSIAK

The Cosmic Poltergeist

Catch-as-catch-can

Aurora Australis over the IceCube Neutrino Observatory at the Amundsen-Scott South Pole Station in Antarctica

ICECUBE COLLABORATION/FRANCIS HALZEN

Deep beneath the South Pole, thousands of detectors, set within a cubic kilometer of ice, lie in wait. While looking up toward the surface, they also peer downward, hoping to catch certain elementary particles from the northern sky that travel through the Earth daily. Nearly all of these elusive particles—called neutrinos—blithely pass through our dense planet like ghosts on the run. Most of the time no signal is registered by the instruments. But on rare occasions a neutrino and a detector collide.

Between 2010 and 2013, this frigid array of detectors, known as the IceCube Neutrino Observatory, recorded some 35,000 neutrinos journeying from the north, a miniscule number compared to the trillions that traversed the Earth over that time. Most of the recorded neutrinos were generated as cosmic rays impacted the northern atmosphere. But a tiny fraction of them appeared to have arrived from events far outside the Milky Way—from either massive stars exploding in distant reaches of the universe, or from the active cores of blazing galaxies. The particles' ultra-high energy, far beyond the levels of the other neutrinos, revealed them for what they were.

With this success at identification, the IceCube detectors offer an entirely new way to survey the cosmos, an endeavor that couldn't have been imagined less than a century ago. Indeed, the very idea of the neutrino was first thought too crazy to be true, the physics equivalent of unicorns or elves. Even more peculiar was where the neutrino's story began: in a German prisoner-of-war camp during World War I.

The British physicist James Chadwick had been studying the phenomenon of radioactivity in Berlin under Hans Geiger (of Geiger counter fame) when the war broke out. Chadwick was soon sent to an internment camp set up at a racecourse just outside the city. To while away the hours of confinement, he began teaching physics to his prison-mate Charles Ellis, a young and sociable cadet from Great Britain's Royal Military Academy who had arrived in Germany on holiday just before the war's unexpected eruption. Together, the two compatriots organized a small research lab in one of the horse stables, an endeavor that was surprisingly tolerated by the camp's senior officials and generously supported by Chadwick's former German scientific colleagues.

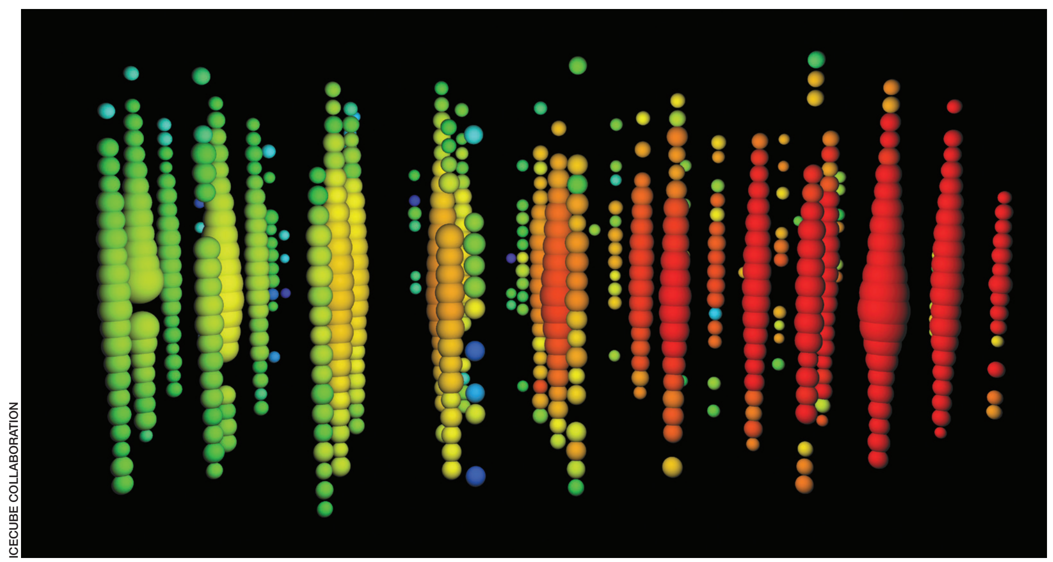
The experience hooked Ellis. After the war, he committed to a career in physics instead of the army and ended up conducting experiments at the famous Cavendish Laboratory in Great Britain, where he studied a troubling anomaly. Whenever a radioactive nucleus decayed by ejecting an electron, something went awry. Ellis and a colleague noticed that the energy of the nucleus before it radioactively decayed was more than the energy of the system afterward (that is, the combined energy of the depleted nucleus and the fleeing electron). It looked as if energy were disappearing, which violated one of the most sacred rules of physics—conservation of energy. Energy can neither be created nor destroyed.

But Wolfgang Pauli, a Viennese physicist, had an abiding faith that atoms were obeying the physical laws of the land, which led him to a radical proposition. In 1930, he suggested that an entirely new particle, invisible to ordinary instruments, could explain the energy discrepancy. Every time a nucleus spewed out an electron, it also emitted a neutral, phantom-like particle that seemed to vanish, carrying away that extra bit of energy and balancing the books.

Usually undaunted by new concepts, Pauli was intimidated by the outrageousness of this idea. "Dear radioactive ladies and gentlemen," he teasingly wrote his friends, then attending a physics conference in Germany. "For the time being, I dare not publish anything about this idea and address myself confidentially first to you, dear radioactive ones, with the question of how it would be with the experimental proof of such a [particle]." He thought of his remedy as "desperate." It wasn't traditionally acceptable for theorists to conjure up particles out of whole cloth, especially particles that seemed impossible to catch.

Not until Chadwick discovered the first known electrically chargeless particle—the neutron—in 1932 did Pauli at last get the courage to officially publish his idea. Soon after, physicist Enrico Fermi dubbed Pauli's hypothetical particle the neutrino, Italian for "little neutral one." The name was apt, for at the time the neutrino was thought to have no mass. According to Pauli's theory, it was nothing more than a spot of energy that flew off at the speed of light.

Despite Chadwick's discovery of the neutron, it took years to prove that neutrinos were more than figments of Pauli's imagination—so long, in fact, that some physicists began to call his particle "the little one who was not there." Pauli had reason to be apprehensive. The neutrino is so oblivious to ordinary matter that it would take a stack of lead, thousands of light-years in length, to stop one in its tracks. Neutrinos bolt through the Earth as if it's no more substantial than a cloudy mist.



ICECUBE COLLABORATION

In October 2010, a high-energy neutrino crossed a detector at the IceCube Neutrino Observatory, leaving this track of light.

But the odds of catching one are considerably increased if there is a flood of such particles coming at you. Indeed, that's how they were finally cornered. In the mid-1950s, physicists Clyde Cowan and Frederick Reines set up a detector outside a South Carolina nuclear power plant and each hour caught a few neutrinos out of the trillions generated by the reactor's core. Receiving news of the verification while attending a conference in Zurich, Pauli celebrated with colleagues by climbing the town's local mountain and enjoying several wine toasts at the top. With a friend on each arm helping him on the way down, Pauli turned to one and remarked, "All good things come to the man who is patient."

About a decade later, physicist Raymond Davis set up the first neutrino observatory in a gold mine, nearly a mile beneath the Black Hills of South Dakota. An underground location assured the measurements would be free from disruptive cosmic rays. In continuous operation for a few decades, Davis's detector kept watch on the torrent of neutrinos flung into the solar system as the Sun burned its nuclear fuel. It provided the first hint that the neutrino had a smidgen of mass after all. More advanced underground observatories constructed in the 1990s provided the ultimate proof, a confirmation that won the lead researchers for the experiments—Takaaki Kajita at the Super-Kamiokande detector in Japan and Arthur McDonald at the Sudbury Neutrino Observatory in Canada—the Nobel prize in physics just last year.

Neutrino detectors and observatories can now be found or are under construction around the globe: not only in Antarctica, Japan, and Canada, but also in France, Russia, Italy, and India. And they are beginning to extend their searches beyond the neutrinos emanating from the Sun to the more powerful particles trekking through the cosmos. While weighing less than a billionth of the mass of a proton, each neutrino we are able to capture will help scientists understand the universe's history, structure, and future fate.

Marcia Bartusiak is professor of the practice in the MIT Graduate Program in Science Writing and the author of six books on astronomy and astrophysics. Her latest are Black Hole: How an Idea Abandoned by Newtonians, Hated by Einstein, and Gambled on by Hawking Became Loved *and* The Day We Found the Universe.