After years of listening with detectors buried in Antarctic ice, IceCube researchers trace neutrino source

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Almost 4 billion years ago, a brilliantly bright galaxy fired a burst of lightweight, fast-moving particles toward Earth (1). Now, an observatory at the South Pole has traced those particles back to their source, potentially solving a century-old mystery about the waves of radiation produced somewhere outside the solar system that wash over our planet each day. But researchers will have to continue to examine the proposed source in multiple wavelengths to ensure they've identified the culprit.

Neutrinos are born from some of the most violent events in the universe, including explosive supernovae and the chaotic environment around supermassive black holes. Tracing neutrinos back to their source can help scientists better understand these destructive events.

Deep in the ice of Antarctica, the IceCube Neutrino Observatory, launched in 2002, hunts for neutrinos, subatomic particles so weak that they usually pass through normal matter undetected (see www.pnas.org/content/111/24/8699). Every second, roughly 100 billion neutrinos pass through 1 square centimeter on Earth, flying at nearly the speed of light. Many of them come from the sun. But the more powerful neutrinos are created outside of the galaxy, generated by a process researchers have only speculated about.

Researchers at the IceCube Neutrino Observatory, launched in 2002, have for the first time been able to trace some of the most energetic neutrinos back to their purported source, the blazar TXS 0506+056. Image courtesy of National Science Foundation/IceCube.

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For the first time, researchers have been able to trace some of the most energetic particles back to their source, the blazar TXS 0506+056. One of the top suspects in the formation of neutrinos, blazars are a class of active galaxy nuclei (AGNs) that form from a supermassive black hole. Although the black hole devours most of the material around it, some of the gas and dust is deflected into powerful jets. The jets carry so much energy that they outshine the stars in the galaxy; astronomers studying blazars can see the jets but not the galaxy itself. The jets accelerate matter, creating neutrinos and the fragments of atoms that create some cosmic rays.

Mysterious Origins

The source of cosmic rays that were discovered in 1912, like the source of neutrinos, has remained a longstanding mystery. The charged particles that produce the radiation interact with magnetic fields on their way to Earth, causing their path to twist and turn. This makes it extremely difficult to trace their origins. But the chargeless neutrinos produced at the same time as their cosmic ray siblings slip through the same magnetic fields, taking a straight-line path to Earth. Hence, the most powerful neutrinos can tell us not only about their home but also about the birth of cosmic rays. "When we make a map of neutrinos, we make a map of cosmic ray accelerators," says Francis Halzen, the principle investigator for IceCube.

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>
> —Imen al Samarai

But the first glimpse of a potential neutrino source remains tentative. By continuing to monitor TXS and the neutrinos that seem to flow from it, researchers hope to forge a stronger link between its activity and the subatomic particles.

Catching neutrinos is not for the faint of heart. Because they are the most weakly interacting known particle, they cannot be detected directly. Instead, researchers hunt for telltale bursts of Cherenkov light, the radiation produced when neutrinos interact with atomic nuclei to create a third charged particle. By tracing the path of the radiation, the researchers can determine from what direction the neutrinos originated.

Since 1960, when Russian physicist Moisei Markov published his idea of hunting for neutrinos by placing detectors in lakes or seas (2, 3), researchers have focused on building Cherenkov detectors in water. But Halzen had an intriguing idea. Instead of water, why not use ice? "I was already thinking about ice for a different reason," says Halzen, who was investigating whether neutrinos produce detectable radio waves when they collided with the material (they do). When he found that the National Science Foundation had a research station at the South Pole, he decided that would be the ideal place. Sometimes called "the godfather of IceCube," Halzen also helped found IceCube's predecessor, the Antarctic Muon and Neutrino Detector Array.

The most important aspect of a Cherenkov detector is the transparency of the medium. In tap water, the blue light of the Cherenkov radiation travels only about 2 meters, Halzen says; in distilled water, the light travels 8 meters. Today, ultrapurification systems allow water to be so transparent that the radiation can travel 80 meters.

IceCube's frozen water is superior to all of these. "The worst ice has a transparency of 100 meters, and in the bottom [of IceCube's detector], it's more than 200 meters," Halzen says. The entire detector spans 1 cubic kilometer of ice.

Most of the neutrinos that wash over Earth are low-energy particles streaming from the sun, too weak for IceCube to detect. Other charged particles form when cosmic rays hit the atmosphere, creating showers that bombard the detector. In 2013, the IceCube team announced that the detector had recorded the signal of high-energy particles that came from beyond the solar system. Before that, only a single event had been known to trigger neutrinos—the violent death of a star.

Supernova 1987a exploded in 1987, and when its light reached our sky, it fired neutrinos toward Earth (4). When the neutrinos were detected, they traced a clear path back to the supernova, suggesting that it was the source. When IceCube was conceived, many had thought that the high-energy neutrinos it captured would originate in supernovae or supernova remnants. But recent IceCube data now seem to suggest that they originate from outside the galaxy—and hence are unlikely to be associated with supernovae.

Earth Under Fire

On September 22, 2017, IceCube captured the footprint of a high-energy neutrino. An automatic notification system alerted other astronomers, some of whom turned their telescopes toward the swath of sky IceCube had identified as the signal's origin. Almost immediately, NASA's Fermi Gamma-ray Space Telescope reported the presence of a previously identified blazar that had brightened over recent months. Other instruments confirmed the potential source.

Blazars are "the overwhelming gamma-ray sources in the sky," notes Fermi team member Sarah Buson, at NASA's Goddard Space Flight Center in Greenbelt, MD. Roughly half the gamma-ray sources spotted by the telescope's Large Area Telescope are blazars, helping make the case for blazars as a potential neutrino source.

But before IceCube, nothing significant stood out about the blazar TXS 0506+056. The blazar's flares, brighter bursts of energy above its usual level, were a common feature and didn't indicate anything unusual. Once Fermi caught sight of the correct region of the sky, "we identified the gamma-ray source as being positionally consistent with [the] neutrinos," Buson says.

For the most part, TXS is just your average AGN. "I would say it's a very typical blazar," Buson says. "There are thousands of sources similar to TXS that share

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similar characteristics." But none of those have been known to produce neutrinos captured by IceCube or other instruments. She did note one peculiarity—TXS is among the 100 brightest blazars detected by Fermi. Only the fact that a path can be traced from the neutrinos detected by IceCube back toward TXS makes it stand out.

In recent months, TXS has been flaring, its already-overpowering brightness increasing. There have been outbursts as the blazar brightens and dims, glowing as much as 100 times stronger than in previous years. Its changes have been observed in the optical, gamma-ray, radio, and X-ray wavelengths, providing a more in-depth coverage than would be available in a single wavelength. Sometimes the mixed observations seem to be connected—a bright flare in the gamma-ray wavelengths may show up in optical, for instance—although at other times they don't seem to be related. Some theories suggest interactions in a blazar's magnetic fields could cause flareups, whereas others suggest they could be produced by stars being gobbled by the central black hole. "The way flares are created—that's still very, very unknown," Buson says.

With TXS identified as a potential neutrino source, Imen al Samarai and other IceCube researchers went back through almost a decade of data to see if the blazar had produced other neutrinos. They hit the jackpot with data recorded at the end of 2014 and beginning of 2015, spotting a burst of 13 individual neutrinos that lasted for several months. They had been cataloged as part of a PhD thesis, but only made up the second-brightest signal, so they were initially overlooked. Buson and her collaborators are investigating Fermi archives to see if TXS produced any compelling gamma-ray activity over the same months. "We are here with the right sensitivity and the right tools to detect these emissions," says al Samarai. "It's the conjunction between these two effects that gave this evidence."

Promising Lead

IceCube researcher Erik Blaufuss points out that the connection between the IceCube neutrino and TXS is still tenuous, although further observations should strengthen the connection. There are so many AGNs in the sky, he says, that "there's a pretty good chance that we point to one." The actual neutrino source could lie behind TXS. Even the 2014 signal doesn't hit what he calls "the gold standard" for results. His hope is that the new article (5), published July 12 in *Science*, inspires other researchers to help put the pieces together.

"Is it the level where we're going to be able to stand on the mountaintop and say, 'yes, we found it'? That's where we fall short," Blaufuss says. "[But] it's a strong candidate for the sources."

But after more than 30 years of hunting, Halzen remains excited. "You cannot imagine how I felt," he says. "You typically look for two neutrinos in 5 years. And suddenly you see 13 in 90 days! You know this just blows you away."

TXS is a promising lead toward understanding how neutrinos and cosmic rays are produced, but it may not be the last. IceCube's automatic notification service, which alerts astronomers about particularly promising neutrino signatures, is only a little over 1 year old, and Blaufuss and his colleagues are continuing to refine it. Right now, it sends out 8–10 heads-ups each year to other astronomers; Blaufuss would like as many as 20. Rapid observations from other telescopes about potential sources will help astronomers gather more information. At the same time, al Samarai and her colleagues continue to review past IceCube observations and match them up to potential sources from existing catalogs by Fermi and other instruments.

IceCube will take an even bigger step over the next decade as it upgrades its systems. Although minor upgrades are already underway, the team hopes to increase the number of detectors in the ice. IceCube-Gen2 would add approximately 80 more detector strings to the 86 existing strings, doubling the size of the instrument and allowing it to potentially collect more neutrinos and, in principle, identify new sources. The team already has funding from its Japanese partners and is hoping to start building by 2022, according to discussions at a May workshop. "TXS is special," Halzen says. "But I cannot believe it's unique, so we will find more just like this."

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3 Berezin VA, Rubakov Valery A, Semikoz DV, eds (1998) *Quantum Gravity: Proceedings of the Sixth Moscow Seminar* (World Scientific, Singapore), p xiv.

4 Krauss LM (1987) Neutrino spectroscopy of supernova 1987A. *Nature* 329:689–694.

5 IceCube Collaboration (2018) Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert. *Science* 361:147–151.

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