

High-energy neutrinos originate in our own galaxy

High-energy cosmic rays, long suspected of interacting with matter in the dense galactic plane, are almost certainly the source of the Milky Way's neutrinos.

The least interactive particles ever observed in the universe are neutrinos. Their neutral charge makes them unaffected by electromagnetism, and their lack of color charge means that they don't participate in the strong force. They are affected by the weak force, but it has an exceedingly short range, roughly the diameter of a proton. With those properties, neutrinos can travel through normal matter more or less undetected—every second, a trillion neutrinos from the Sun pass through your hand.

The lack of interactions makes neutrinos an ideal messenger of information on various astrophysical processes (see, for example, “The elusive Glashow resonance was observed deep within Antarctic ice,” *PHYSICS TODAY* online, 8 April 2021, and the article by Francis Halzen and Spencer Klein, *PHYSICS TODAY*, May 2008, page 29). Because neutrinos don't interact much with other matter, their detection can be used to trace the direction from which they came and to reconstruct the events that produced them.

Most astrophysical neutrinos seen so far have come from somewhere beyond our galaxy. But now the IceCube Collaboration has identified a high-energy neutrino flux in the Milky Way that originates predominantly in the galactic plane.¹ The finding reinforces previous theoretical hypotheses about the origins of cosmic rays. It also shows how multiple messengers—neutrino measurements, gamma-ray emissions, and other radiation—can be used together to better investigate our own galaxy.

A muddled path

Cosmic rays are high-energy particles that move through space with an energy



FIGURE 1. CHERENKOV RADIATION. High-energy neutrinos racing through Earth's atmosphere sometimes reach the IceCube Neutrino Observatory in Antarctica and collide with the nuclei of frozen water molecules. The impact produces charged particles that, if energetic enough, travel faster than the speed of light in ice, yielding blue-hued Cherenkov radiation. The optical sensor in the foreground and the dozens more in the background of this artistic illustration are a fraction of the thousands that hang on cables drilled as deep as 2500 m into the ice. By measuring the radiation and its trajectory, researchers estimate the neutrino's arrival direction and its intensity. (Courtesy of the IceCube Collaboration.)

range that roughly spans from a few GeV to several PeV, although most have energies on the lower end of the range. They're constantly bombarding Earth's atmosphere and are responsible for some chip-level errors that can flip the value of memory cells in electronic devices. Outside the planet's protective atmosphere and magnetic field, the highly ionizing radiation poses dangerous acute

and chronic health risks for astronauts.

Even if space technology advances enough to quickly and reliably carry people to Mars and beyond, cosmic rays may limit how long and thus how far humans can travel through space, if the shuttles lack radiation-hardened shielding. (See the Quick Study by Larry Townsend, *PHYSICS TODAY*, March 2020, page 66.)

Despite their discovery more than 100

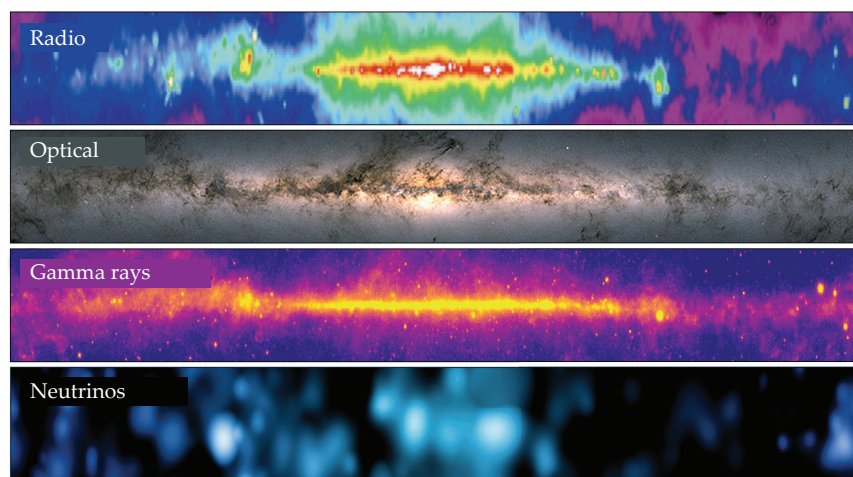


FIGURE 2. NEUTRINO VISION. For years, astronomers have viewed the Milky Way through radio, optical, and gamma-ray emissions. Images taken with all three clearly show the galactic center and surrounding plane. After carefully analyzing 10 years of data from the IceCube Neutrino Observatory, an international collaboration found that the Milky Way is a source of neutrinos, and the diffuse neutrino signal across the galaxy, shown here, is statistically consistent with gamma-ray emission. (Courtesy of the IceCube Collaboration.)

years ago, cosmic rays remain mysterious. Astronomers do know that some GeV cosmic rays originate from the Sun's coronal mass ejections and other solar eruptions. But the theoretical hypotheses for where the high-energy flux comes from—supermassive black holes, active galactic nuclei, supernovae, or something else—are difficult to evaluate with much statistical certainty because of what happens to the cosmic rays as they travel through space.

Along their path to Earth, high-energy cosmic rays often encounter strong galactic magnetic fields, which scramble their trajectories so much that it's impossible to determine where they came from. Some of the cosmic rays interact with the gaseous interstellar medium and produce particles whose trajectories are easier to track. Those interactions produce both charged and neutral pions. Neutral pions quickly decay and most commonly produce gamma rays. Although observations of the gamma-ray emission hint at where cosmic rays come from, the evidence isn't conclusive because gamma-ray photons are readily absorbed by other matter in the interstellar medium. One solution to the origin question comes from the other product of cosmic-ray interactions: charged pions, which produce neutrinos.²

Under the ice

Most visible mass in the Milky Way lies

in its galactic plane, and in the interstellar space, hydrogen nuclei are spread out at an average density of one per cubic centimeter. When cosmic rays interact with interstellar hydrogen, gamma rays are produced; and they've already been observed by the Large Area Telescope aboard NASA's *Fermi Gamma-Ray Space Telescope*. The cosmic-ray interactions also make neutrinos, which are most visible in Earth's southern sky if atmospheric noise is minimized, according to calculations of the estimated neutrino flux. In part for that reason, the Amundsen–Scott South Pole Station in Antarctica hosts the IceCube Neutrino Observatory.

The detector is a cubic kilometer of ice with more than 5000 spherical optical sensors, which hang on cables drilled as deep as 2500 m. Most neutrinos pass through the detector area without interacting, but when one slams into a water molecule, it produces muons and other charged particles. If any of them are energetic enough, they travel faster than light does in the ice, which results in the emission of blue-tinged Cherenkov radiation, as illustrated in figure 1. (The effect is similar to the sonic boom that's heard when a supersonic jet travels faster than the speed of sound.)

By measuring the Cherenkov radiation picked up by the optical sensors and the blue light's spatial pattern, researchers can infer the particle's energy and from what direction it arrived. One of the

biggest challenges, however, is the overwhelming number of neutrinos and muons produced in Earth's atmosphere by cosmic rays. For every astrophysical neutrino that IceCube observes, the facility measures 100 million atmospheric muons.

To filter the immense background noise from the astrophysical neutrino signal, the IceCube Collaboration has developed an event-selection protocol. A neutrino signal measured by IceCube is categorized either as a track event, in which a neutrino creates a muon that then leaves an energetic trail as it races through the ice, or as a cascade event, in which the neutrino releases most or all of its energy at a single location. Many atmospheric neutrinos leave track events in the IceCube detector, so selecting for just cascades greatly reduces the background noise.

The approach is computationally expensive. Many neutrino events need to be excluded, including those found in certain detector regions that are known to witness many atmospheric muons and neutrinos with energies close to those of atmospheric neutrinos. The exclusions have left the IceCube Collaboration with a high-quality data set that it has used for previous analyses—for example, in 2013, the team discovered an extragalactic source of neutrinos.³ The data set, however, was too small to draw conclusions with high statistical confidence about galactic neutrino emission.

Deep learning

To better analyze the 10 years of data collected from IceCube so far, the collaboration developed a hybrid artificial-intelligence technique, spearheaded by Mirco Hünnefeld of the Technical University Dortmund and Steve Scifani of Drexel University.⁴ The first part of the technique uses a deep-learning neural network to identify cascade neutrino events. The neural network runs through the data quickly, and the resulting time savings allows more events, including those at the lower end of the energy range, to be included in the data set. Compared with earlier analyses, the neural network also improves by a factor of two the angular resolution of the direction of incoming neutrinos.

The second part of the technique uses the light patterns collected by the detectors to reconstruct the neutrino's direction

and energy. The previous reconstruction method was based on a computationally expensive set of Monte Carlo simulations, but the neural network approximates those simulations more efficiently. The new data set of 60 000 neutrino events is 20 times as large as previous sets. Francis Halzen, a theoretical physicist who is a member of the IceCube Collaboration, says that “given the new machine-learning techniques, it almost looked easy in retrospect, especially given our unsuccessful efforts to see our galaxy over the last decade.”

With those improvements, the collaboration found a signal of diffuse high-energy neutrinos from the galactic plane. Figure 2 shows the Milky Way as it’s typically been seen through radio, optical, and gamma-ray emissions. Those three wavelength regimes show a clear, bright galactic center flanked on either side by a thin plane of more diffuse emission. The Milky Way’s neutrino signal is about 10% of the total flux at 30 TeV, and although it may not be immediately clear,

the signal is consistent with the gamma-ray emission. In fact, the IceCube Collaboration found that the chance for the neutrino signal to arise randomly from background noise is less than 1 in 100 000, or a statistical confidence level of 4.5 standard deviations.

Guide to the galaxy

The neutrino picture of the Milky Way so far shows a diffuse pattern of emission that arises when cosmic rays interact with interstellar gas. But neutrinos could be coming from galactic point sources of cosmic rays. To figure that out, the team will need to review more data. Similar to how the atmospheric background overwhelms the astrophysical signal, the suspected point-source neutrino signal may be masked by the diffuse neutrino signal shown in figure 2.

Astronomers already have some ideas for where galactic cosmic rays, and by extension neutrinos, could come from. Supermassive black holes could produce them (see PHYSICS TODAY, August 2022,

page 14), but the one at the center of the Milky Way may not be active enough to generate such high-energy particles.

Neutrinos could also be sourced from active galactic nuclei (see “IceCube pinpoints an extragalactic neutrino source,” PHYSICS TODAY online, 12 July 2018), and some have already been spotted in an extragalactic supernova (see “A supernova for the ages, 30 years later,” PHYSICS TODAY online, 23 February 2017). In the Milky Way, says Halzen, “finding the sources are our next priority, and we are on it.”

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References

1. IceCube Collaboration, *Science* **380**, 1338 (2023).
2. M. Ackermann et al., *Astrophys. J.* **750**, 3 (2012).
3. IceCube Collaboration, *Science* **342**, 947 (2013).
4. M. Hünnefeld (on behalf of the IceCube Collaboration), *Proc. Sci.* (2017), <https://pos.sissa.it/301/1057/pdf>.

Toward faster, safer proton therapy

Most facilities for zapping tumors with protons are extremely inefficient. But perhaps they don’t have to be.

In the fight against cancer, the global medical community is placing an increasingly big bet on protons. Of the just over 100 proton-therapy facilities worldwide, more than half began operation in 2016 or later. Currently they treat some 50 000 patients per year, with a cumulative total of around 300 000.

The treatments are eye-wateringly expensive. A new facility can cost more than \$200 million just to build, not counting the cost of upkeep, operation, and doctors’ time. Because of the high price tag, plenty of critics are putting pressure on proton-therapy proponents to justify the expense with results. (See, for example, PHYSICS TODAY, October 2015, page 8.) For some applications—such as treating eye tumors, as shown in figure 1—proton therapy has shown clear advantages over other treatments. For others, achieving its potential is still a work in progress.

At the Paul Scherrer Institute in Switzerland, home to one of the oldest operating proton-therapy centers, a team of researchers led by Vivek Maradia and

his PhD adviser, Serena Psoroulas, is working to lessen a major source of inefficiency: In a typical treatment facility that accelerates its protons with a cyclotron, between 70% and 99.9% of the accelerated protons get thrown away.¹

Wasted protons don’t directly translate into wasted dollars. But getting protons more efficiently into patients could lead to faster treatments, happier patients, and eventually more economical facilities. And it could allow proton therapy to better benefit from a powerful but counterintuitive phenomenon called the FLASH effect: Delivering a lot of radiation to a tumor all at once could lessen the side effects on the surrounding healthy tissue.

Low transmission

Proton therapy’s appeal stems from the physics of how protons interact with matter. The goal of radiotherapy—and indeed of all forms of cancer treatment—is to kill cancer cells while sparing healthy ones. But a beam of radiation (of any

form) sent into the body encounters not just the tumor but also the healthy organs in front of and behind it. X rays, still the tool for most radiotherapy, deposit their energy everywhere along their path, in tumor and healthy cells alike.

Protons, on the other hand, have scattering cross sections that depend inversely on their kinetic energy. So a proton passing through the body slows down little by little, until it finally leaves most of its energy—and does most of its damage—right before it stops. By controlling the proton beam’s direction and initial kinetic energy, clinicians can position the radiation-affected region in all three dimensions.

In practical terms, however, controlling proton kinetic energies is not so easy. Clinicians need proton energies ranging from 60 MeV (for tumors close to the body surface, such as those in the eyes) to 230 MeV (for tumors tens of centimeters deep in the body). But a single cyclotron produces proton beams at just one energy. It would be far too expensive to have a separate cyclotron for every possible proton energy. A few facilities have opted for low-energy cyclotrons for