

Astrophysical HIGH-ENERGY NEUTRINOS

Peter Mészáros

News from multiple messengers—
neutrinos, cosmic rays, and photons—
provides clues to the cosmic sources
that create some of the most energetic
particles observed on Earth.

The IceCube Neutrino Observatory.
(Courtesy of the IceCube collaboration.)

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Wolfgang Pauli proposed the existence of neutrinos in a letter addressed to the “Dear Radioactive Ladies and Gentlemen” assembled at the 1930 Solvay Conference in Belgium. The particles, he reasoned, would enable energy and momentum to be conserved in the beta decay of radioactive nuclei; never mind that a neutrino had never actually been observed. Later, in a letter to a friend, Pauli lamented, “I have done a terrible thing. I have postulated a particle that cannot be detected.”

Neutrinos were subsequently detected, but due to their extremely small interaction cross section, that did not happen until the mid 1950s. The observation of the neutrino opened the way for probing the nuclear processes that had been theoretically predicted to be responsible for powering the luminosity of stars, the explosions of supernovas, and the synthesis of all but the lightest elements in the universe.

Neutrinos close to home

The most obvious neutrino source is the Sun. Neutrinos are created there in the simplest nuclear fusion reaction, in which two protons combine to make a deuterium nucleus whose formation is accompanied by the emission of a positron and a neutrino. All the other, more complex reaction chains that lead to heavier elements also produce neutrinos that immediately escape the Sun, essentially at the speed of light; those same processes, incidentally, are the source of the light emitted by stars.

Solar neutrinos were first observed by Raymond Davis Jr and colleagues in a 1960s experiment that used 600 tons of cleaning fluid (perchloroethylene). Located in a tank deep underground in the Homestake mine in South Dakota, Davis’s detector measured a reaction whereby a solar neutrino hitting a chlorine nucleus in the cleaning fluid becomes an argon nucleus. The results he obtained were verified by Masatoshi Koshihara and collaborators, whose experiment featured a 3000-ton water Cherenkov detector in the Kamioka mine in Japan. For their achievements in launching neutrino astronomy, Davis and Koshihara shared the 2002 Nobel Prize in Physics (see *PHYSICS TODAY*, December 2002, page 16).

Neutrinos are also created in Earth’s atmosphere by cosmic rays, high-energy particles—mostly protons and nuclei—that reach us from outer space. Upon hitting nuclei in the atmosphere, cosmic rays initiate reactions similar to those observed in terrestrial high-energy particle accelerators such as the Large Hadron Collider in Switzerland. Physicists have known for some time that such nuclear reactions result not only in the type of neutrinos produced in the Sun, called electron neutrinos, but also in two other types, or flavors: muon neutrinos and tau neutrinos. The Kamiokande detector in Kamioka was capable of detecting solar electron neutrinos and electron and muon neutrinos produced in the atmosphere. Curiously, the number of electron neutrinos observed from the Sun was about 40% less than predicted from the accepted theory of stellar structure.

The resolution of the discrepancy lies in a particle-physics phenomenon called neutrino oscillation. After traveling a long distance through space or through a medium, a neutrino created in a particular flavor can “oscillate” into another one. The electron neutrinos missing in the Kamiokande experiment had simply changed into neutrinos of another flavor. To recognize the demonstration of the effect of neutrino oscillations, the 2015 Nobel Prize in Physics was awarded to Arthur McDonald of Queen’s University in Canada and Takaaki Kajita of Tokyo University, the leaders, respectively, of the Sudbury Neutrino Observatory and Super-Kamiokande collaborations (see *PHYSICS TODAY*, December 2015, page 16).

Once the neutrino-creating fusion reactions in stars have produced all the elements up to iron, exothermic reactions are no longer possible. The

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lack of heat input to provide pressure support results in the gravitational collapse of the stellar core, during which neutrinos are produced again as protons and electrons combine in inverse beta decay. The collapse continues until the density in the core is close to that in a nucleus, at which time a gigantic burst of activity produces all flavors of neutrinos. That production is accompanied by a reversal of the collapse and a resulting shock wave that starts to propagate outward. The consequent sudden and spectacular optical brightening by many orders of magnitude is known as a core-collapse supernova. In one particular supernova, SN1987a, the neutrino burst that preceded the optical brightening was detected by independent groups at the Kamiokande, Irvine-Michigan-Brookhaven, and Baksan underground neutrino detectors.

Evidence for extragalactic neutrinos

Solar, stellar, and supernova neutrinos typically have energies in the range of 1–30 MeV. In 2013 researchers at the IceCube Neutrino Observatory, shown on page 36, announced that they had spotted a diffuse flux of neutrinos with energies many orders of magnitude higher,¹ up to a peta electron volt (10^{15} eV). Subsequent measurements² extended the energies down to tens of TeV. IceCube, the instrument responsible for those extraordinary detections, consists of a cubic kilometer of ice, instrumented with phototubes that detect the light produced by neutrinos interacting with particles in the ice. Roughly a gigaton in mass, IceCube sits 1.5 kilometers beneath the Antarctic surface near the South Pole. (For more on IceCube and other neutrino detectors, see reference 3 and the article by Francis Halzen and Spencer Klein, *PHYSICS TODAY*, May 2008, page 29.)

IceCube's discovery of high-energy neutrinos—by which I mean above 1 GeV in energy—caused great excitement for a couple of reasons. First, the energy spectrum of the neutrinos departed significantly from that of the atmospheric neutrinos. As shown in figure 1, atmospheric neutrinos have a well-measured energy distribution that follows a steep power law. The high-energy neutrino flux discovered by IceCube displays a much flatter power law and diverges significantly from the atmospheric neutrino background at energies beyond about 100 TeV.

Second, the approximately isotropic arrival directions of the high-energy neutrinos suggested an extragalactic origin. Moreover, IceCube was designed to be able to detect neutrinos of all three flavors, and the mix of flavors it measured is compatible with the neutrinos having oscillated as they traveled on an intergalactic journey to Earth.

To be sure, the precision in the arrival direction of each individual neutrino is fairly poor when compared to the high angular resolution achieved by electromagnetic detectors such as optical telescopes. The directional uncertainty depends on the energy and flavor of the neutrino, as different types of neutrinos interact differently with the detector. For muon neutrinos the IceCube error is upwards of 0.4 degrees of arc, whereas for electron neutrinos it is currently 15–30 degrees of arc, although the electron uncertainty should decrease in the future as analy-

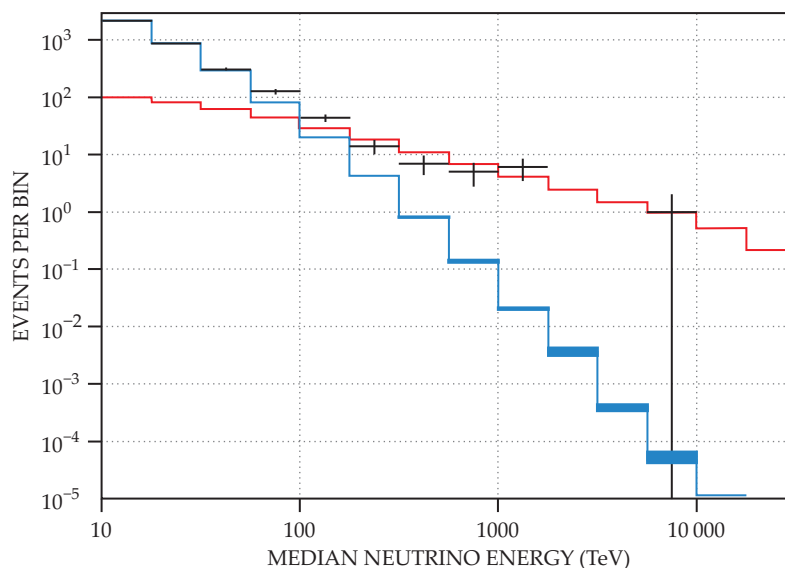


FIGURE 1. ICECUBE'S NEUTRINO MEASUREMENTS (black crosses) show that the flux of high-energy, astrophysical neutrinos diverges significantly from the flux of atmospheric neutrinos (blue). The red stepped line is a power-law fit to the atmospheric component. (Adapted from ref. 18.)

sis techniques improve. The fuzzy angular localization means that attempts to associate neutrinos observed on Earth with specific types of galactic or extragalactic sources has so far proven fruitless—with one notable exception, to be discussed later.

Sources of high-energy neutrinos

Transitions within a nucleus cannot produce neutrinos at GeV energies and above. Neither can thermal processes inside stable, collapsing, or exploding stars, where temperatures reach at most a few tens of MeV. The only uncontroversial way to make them is via highly relativistic charged particles colliding with either target particles or photons. The cosmos has an ample supply of such relativistic particles: cosmic rays, which have been detected by various independent experiments at energies ranging from the GeV scale to well beyond that of the highest-energy neutrinos so far confidently detected.

Cosmic rays with energies less than about 1 PeV are thought to be accelerated in supernovae; the origin of those with energies in the 1– 10^5 PeV range is uncertain. Cosmic rays with energies between 1 PeV and, say, 100 PeV can produce neutrinos in the high-energy range observed by IceCube if they undergo so-called Fermi acceleration in sources with a sufficiently large density of, for example, thermal protons or photons. In that case, the proton–proton or proton–photon interactions that produce the neutrinos also lead to neutral pions that decay into gamma rays.

Physicists trying to formulate a model of astrophysically reasonable and eventually identifiable sources of high-energy neutrinos face a formidable challenge: They need to come up with an appropriate cosmic-ray acceleration site that produces a neutrino flux with the proper spectrum without violating the constraints imposed by observations of gamma rays⁴ and the diffuse cosmic-ray flux. Addressing that challenge is a poster-child problem for multimessenger astronomy, which involves several types of information-carrying messengers, as shown in

figure 2. The photons, cosmic rays, and neutrinos illustrated there are the results, respectively, of electromagnetic, strong, and weak interactions of elementary particles.

Astrophysical theorists have devised various generic sources that could accelerate cosmic-ray protons to energies up to about 100 PeV with a power-law energy spectrum $dn/dE \propto E^{-s}$, where the spectral index s is in the 2.0–2.2 range, as expected for the diffusive Fermi acceleration of particles bouncing across a nonrelativistic shock. Such cosmic rays interacting with proton targets can produce a diffuse neutrino flux having a spectral index consistent with the IceCube data, along with a corresponding diffuse gamma-ray flux.⁵

A rogues' gallery of possible sources

What in the heavens can be producing these neutrinos? Here I discuss the major candidates; for additional detail see reference 6.

► **Active galactic nuclei.** Roughly 1 in 10 galaxies shows evidence of nonthermal radio, optical, or more energetic radiation coming from its nuclear region, called an active galactic nucleus (AGN; often the entire galaxy is called an AGN). Those emissions are generally understood to be the consequence of gas accretion by a massive black hole at the galactic center. A smaller fraction of galaxies—less than 1%—show jets of RF-emitting plasma extending well beyond the galaxy's stellar component. The plasma jets of those radio-loud AGNs produce cosmic-ray electrons and protons and an intense flux of non-thermal photons extending in frequency from the radio band up to, in some cases, gamma rays.

Blazars are a type of radio-loud AGN whose jets point toward Earth. The energies of their cosmic rays appear to be sufficiently high that the particles can interact with the galaxy's photons and thermal protons to produce charged and neutral pions. The charged pions' decay leads to high-energy neutrinos; the neutral pions produce high-energy gamma rays that are degraded during their intergalactic travels by interactions with the diffuse IR background. Eventually those photons cascade down to the sub-TeV energy range detectable by the *Fermi*

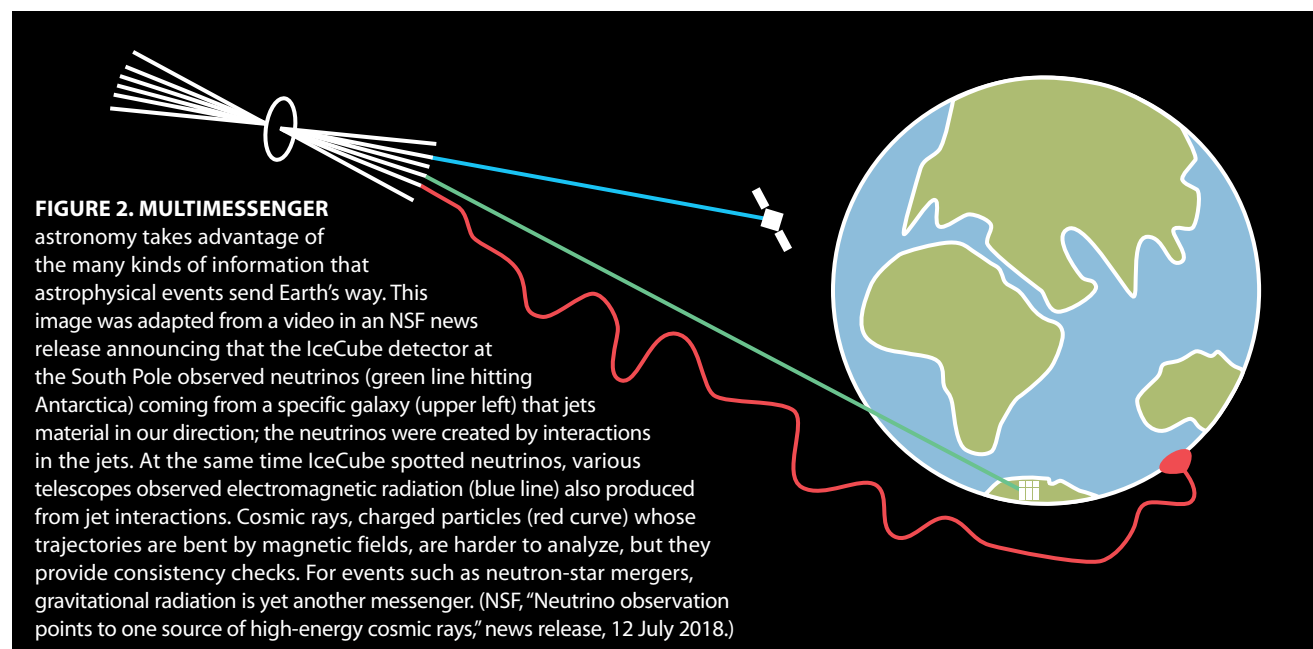
Gamma-Ray Space Telescope. In fact, *Fermi* studies attribute roughly 85% of their observed diffuse isotropic gamma-ray background flux to blazars.⁷

The energetics of the blazar jets might explain the observed flux of highest-energy cosmic rays, but it is uncertain how much blazars can contribute to the diffuse high-energy neutrino background. One reason is that the density of photons and thermal nucleons in the jets is low, so the chances of a relativistic cosmic ray impacting one of those targets to produce pions is also low. More importantly, attempts to find angular coincidences between observed high-energy neutrino directions and the known population of blazars had yielded no significant correlation until a few months ago, although admittedly those efforts relied on uncertain assumptions about the neutrino spectrum. The single and exciting exception is the blazar TXS 0506+056, discussed below.

► **Galaxy clusters.** Most galaxies and AGNs live in clusters of galaxies. Thus, even if cosmic rays accelerated in galaxies or AGNs do not have time to produce neutrinos near where they are created, all is not lost. After the cosmic rays escape from their birthplace, they will scatter off magnetic-field irregularities in the intracluster gas until they random-walk their way out of the cluster. During that period of scattering, the cosmic rays have additional chances to collide with protons and produce the pions that decay into high-energy neutrinos and gamma rays.

Two other mechanisms in clusters can accelerate cosmic rays to energies as high as 100 PeV. One is based on the shock created as external gas accretes onto the cluster; the other relies on shocks that arise from collisions between galaxies in the cluster. High-energy proton–proton collisions then lead to neutrinos with energies up to 5 PeV, comparable to the maximum energies so far observed by IceCube.

Galaxy clusters are optically thin—not only do neutrinos escape freely, but so do gamma rays—and that turns out to argue against attributing the observed IceCube flux to clusters. The gamma rays that escape are degraded by gamma–gamma



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interactions on their way to Earth, as described earlier, and appear in larger numbers at energies below 1 TeV. *Fermi* observations do indicate a diffuse gamma-ray flux at those relatively low energies. But 85% of the flux is accounted for by contributions from blazars and other AGNs, which leaves only 15% for other sources. However, analysis of the pion production in proton–proton and proton–photon interactions indicates that the energy fluxes of gamma rays and neutrinos should be similar. Thus if clusters were the exclusive source of the observed neutrino flux, they would also produce a non-blazar gamma-ray flux about sevenfold what is observed.

► **Starburst galaxies.** During its lifetime, a typical galaxy undergoes spurts of increased star formation in which it produces 10 or more solar masses of stars each year. At any given time, about 1% of all galaxies are in such a starburst phase, which can last more than 10 million years. The newly formed massive stars undergo fusion reactions until they have exhausted their nuclear fuel. Once a star is out of fuel, its core collapses under the pull of gravity; eventually the star explodes as a supernova.

The average core-collapse supernova converts several times 10^{46} J of gravitational energy into thermal 1- to 30-MeV neutrinos that escape. In addition, the explosion deposits about 10^{44} J of kinetic energy into the supernova's outer stellar envelope, whose matter is ejected with velocities around 10% of the speed of light. As the ejected material plows into the interstellar gas, it creates shocks that are thought to accelerate cosmic rays. As was noted more than a decade ago,⁸ the amount of energy in the accelerated cosmic rays of starburst galaxies could provide a flux of TeV–PeV neutrinos of the order of what was subsequently detected by IceCube (see figure 3). Like clusters, however, starburst galaxies are optically thin and would produce too high a nonblazar gamma-ray flux if they were responsible for the high-energy neutrinos observed by IceCube.

► **Gamma-ray bursts.** Roughly once a day, space-based detectors observe an intense flash of gamma rays signaling a cataclysmic celestial event that produces as much energy in a few seconds as our Sun puts out in 10 billion years. Those gamma-ray bursts (GRBs) result either from the core collapse of a rare type of massive star or from the merger of a neutron-star binary. The consensus picture is that the collapse of the rapidly rotating core or the merger leads to a central black hole or a heavy neutron star. The surrounding accretion disk produces a highly relativistic jet, in which shocks or magnetic dissipation accelerates electrons and produces nonthermal gamma rays. Protons may also be accelerated up to cosmic-ray energies, and proton–photon interactions between those cosmic rays and the gamma rays produced by the GRB lead to neutrinos with energies in the TeV–PeV range.⁹

With the plausible assumption that the energy in accelerated protons is comparable to that of the electrons, one can predict the high-energy neutrino flux given the observed flux of gamma rays from GRBs. Based on its search for neutrinos coincident with GRBs, the IceCube team has concluded that less than 1% of the astrophysical neutrino flux comes from observable GRBs.¹⁰ The simple models used in the analysis have some uncertainties, but the IceCube result calls into question the assumption that the proton and electron energies are comparable.

In obtaining their negative result, the IceCube team assumed that GRBs are of the “classical” type, meaning that their jets

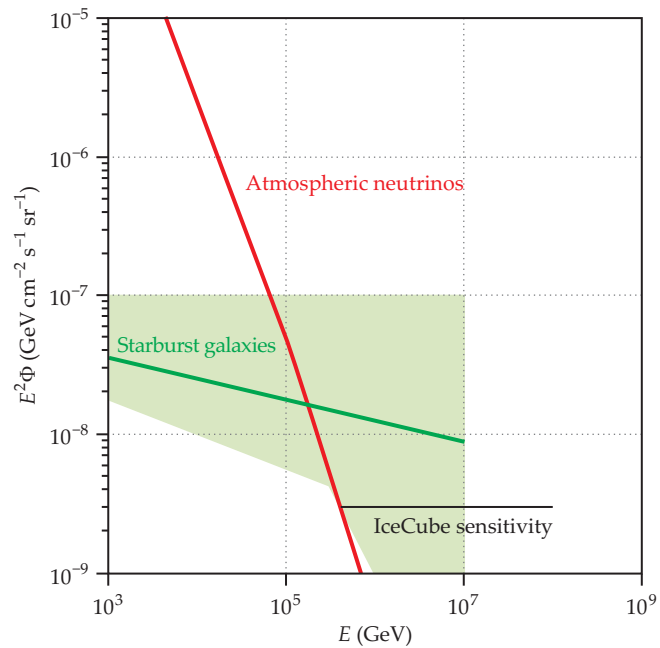


FIGURE 3. THE STARBURST NEUTRINO FLUX, according to a 2006 theory paper by Abraham Loeb and Eli Waxman, is approximately consistent with subsequent IceCube observations. In this plot the green area represents possible neutrino flux Φ as a function of energy E . The upper boundary corresponds to a cosmic-ray spectral index s (see main text) of 2.0, and for $E < 10^{5.5}$ GeV, the lower boundary corresponds to $s = 2.25$. IceCube data are consistent with a spectral index in the range of 2.0–2.2 for energies in the range of 10^5 – 10^7 GeV or so; for lower energies, the measured flux is a somewhat steeper function of energy. The solid red line shows the atmospheric neutrino background. The black horizontal line indicates the observed sensitivity of IceCube. (Adapted from ref. 8.)

emerge clear of the stellar envelope and radiate a substantial amount of observable gamma rays. It may be, however, that for every jet that successfully emerges, many more do not. The gamma rays produced by those choked jets are fully or mostly reabsorbed by the stellar debris.¹¹ In a less extreme scenario, a jet just barely manages to escape the stellar envelope before exhausting itself; in that case gamma radiation is produced but is much weaker than in a classical GRB. As shown in figure 4, the choked or barely emerging jets still produce high-energy neutrinos that could be detected by IceCube even if the accompanying gamma radiation is very difficult or impossible to detect.¹² A follow-up IceCube study indicates that such nonclassical GRBs could contribute substantially to the high-energy neutrinos observed by the collaboration.¹³

Prospects and an exciting observation

The small number of TeV–PeV neutrino events currently being collected by IceCube and other detectors makes it difficult to associate neutrinos with specific sources, unless by rare chance the source happens to be very near Earth. Astrophysicists have observed the diffuse neutrino flux from many sources, but choosing from among the various neutrino production models based solely on the neutrino spectrum is an arduous task. Furthermore, determining the spectrum in the first place requires lots of observation time.

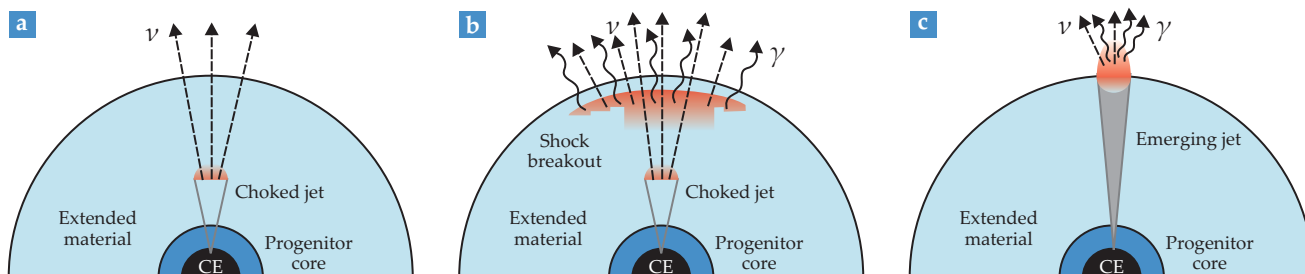


FIGURE 4. A CHOKED OR NEARLY CHOKED JET from a gamma-ray burst (GRB) produces neutrinos but little or no electromagnetic radiation. The jet is powered by a central engine (CE), the black hole or neutron star and surrounding accretion disk that lie at the center of the GRB. **(a)** If the jet is choked near the progenitor core of stellar matter surrounding the engine, all the electromagnetic radiation it generates is reabsorbed by the GRB's extended material (light blue). **(b)** A barely choked jet produces a shock wave that just breaks out from the GRB surface and produces some electromagnetic radiation. **(c)** A jet that barely emerges from the GRB produces electromagnetic radiation, but much less than is created by the classical GRBs whose jets fully emerge. (Adapted from ref. 12.)

Distinguishing between the various possible neutrino sources will remain difficult, unless researchers can obtain significant correlations between high-energy neutrinos and the gamma rays expected to be associated with them. Even when gamma radiation is degraded to sub-TeV energies by photon-photon interactions, its spectral flux can be estimated and provides an important constraint. Even stronger constraints can be obtained in principle if the neutrinos and the gamma rays are produced in roughly contemporaneous flaring episodes, either in a one-time event or in repeating events, since observers can hope to exploit the coincidences in position and time of the different messengers. Unfortunately, efforts to correlate neutrino detections with known sources of electromagnetic radiation will remain difficult as long as the neutrino location uncertainties are at best on the order of a degree—a span that encompasses a large number of possibilities.

The detection of other messengers besides neutrinos and photons would, of course, be even more helpful. The cosmic rays associated with neutrino production cannot be traced back to individual sources; their trajectories are altered by the random magnetic fields in intergalactic space, and as a result, they arrive much later and from different directions than do the photons and neutrinos. At least globally, however, the total diffuse cosmic-ray flux must be compatible with the observed neutrino flux.

Some cosmic events emit a different kind of messenger: gravitational waves. Last year, the Laser Interferometer Gravitational-Wave Observatory and VIRGO collaborations detected gravitational radiation from GW170817, a source that produced a coincident gamma-ray flash and that later displayed an x-ray, optical, and RF afterglow.¹⁴ Together, the gravitational and electromagnetic messages

enabled GW170817 to be identified as a GRB arising from the merger of a binary neutron star. No associated high-energy neutrinos were detected, although that is not surprising. The expected fluxes would have been hard to detect with IceCube, though they may be within reach of future generations of neutrino detectors,¹⁵ such as the proposed IceCube-Gen2.

The complicated business of weaving together the information gleaned from different types of instruments that observe different types of messengers requires a careful analysis of how the sensitivity and noise of the various instruments interrelate. An ambitious effort along those lines is the Astrophysical Multimessenger Observatory Network. (See reference 16 and

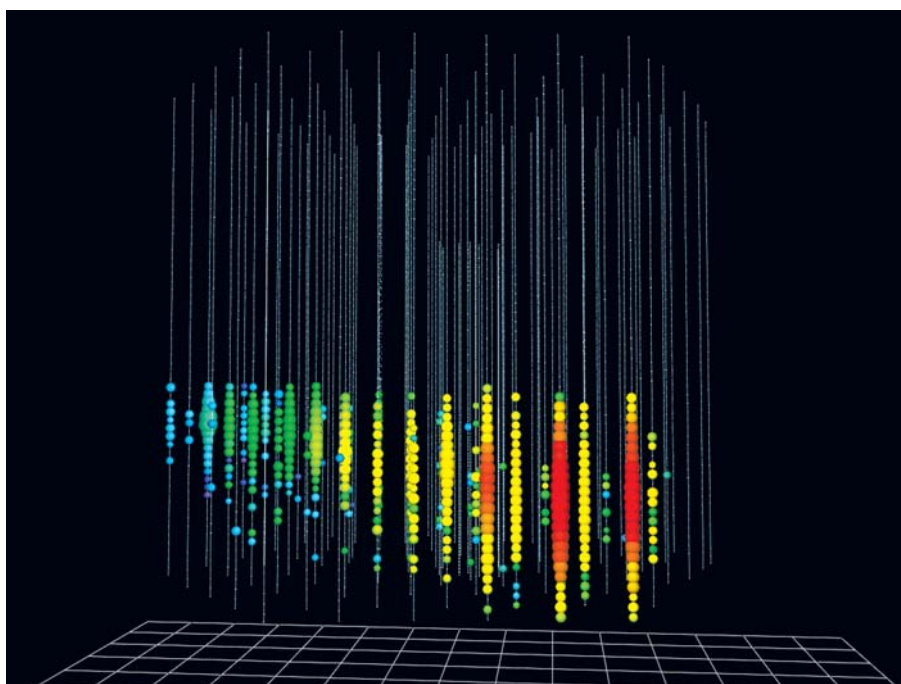


FIGURE 5. A TRACK OF CHERENKOV RADIATION pointing to the blazar TXS 0506+056 was detected by IceCube on 22 September 2017. A high-energy neutrino from the blazar interacted with Antarctic ice and ultimately generated the light seen by IceCube's underground photodetectors. Each circle indicates a photodetector. Size corresponds to the number of photons observed; color indicates time (red is earliest; blue, latest). The event determined the direction of the neutrino source to better than 1° accuracy. (Courtesy of the IceCube collaboration.)

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PHYSICS TODAY, September 2015, page 27.) AMON has signed memorandums of understanding with more than a dozen observatories that together gather news from all four different types of messenger. It aims not only to centralize and instantly disseminate the alerts from individual observatories, but also to exploit the fact that a combination of coincidental subthreshold triggers from multiple observatories can rise above the threshold level.

Earlier this year, IceCube and some 20 telescopes combined forces¹⁷ to establish a spatial and time coincidence between the production of a 300 TeV neutrino observed at IceCube and the generation of gamma-ray flares observed from the blazar TXS 0506+056 (see figure 5). Although the 3- to 4-standard-deviation statistical significance of the result is below the 5 standard deviations conventionally required for high confidence, the achievement is the first time an identified object has been claimed as the source of high-energy neutrinos, and it may herald a new and exciting era in multimessenger astrophysics.

Researchers are working to understand why previous efforts to determine correlations between high-energy neutrinos and other blazars have not reached the level of significance achieved with TXS 0506+056. In any event, preliminary analyses suggest that blazars such as TXS 0506+056 may not be able to account for most of the high-energy neutrinos observed to date, so more exciting news may be on the horizon. High-energy neutrino detectors already have excellent timing accuracy, and their efficiency is increasing. Electromagnetic detectors do an excellent job at pinpointing source locations. The strategy of paying attention to multiple messengers bringing news from the sources of astrophysical high-energy neutrinos will not only

allow astrophysicists to unmask those sources, it will also provide a much better understanding of the physics powering those and related objects inhabiting the cosmos.

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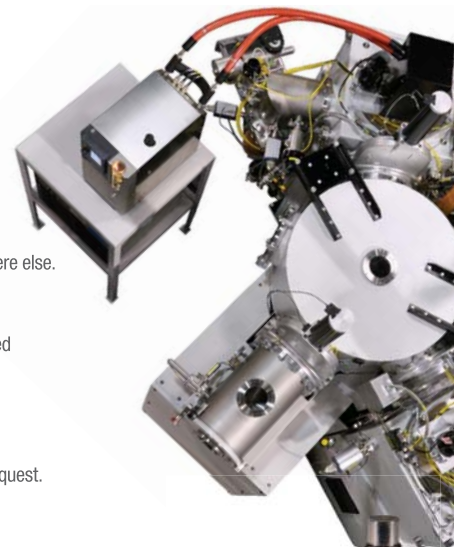
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