A star's demise is connected to a neutrino outburst

The most conclusive evidence to date demonstrates that high-energy neutrinos could be formed by tidal forces that rip apart a star near a supermassive black hole.

FIGURE 1. A TIDAL DISRUPTION EVENT occurred when a star much larger than the Sun traveled too close to the supermassive black hole in the center of a galaxy 4.4 billion light-years away from Earth. In this illustration, radiation from the tidal disruption at the center vaporized the dust in its immediate vicinity. The more distant, red-colored dust half a light-year away heated up and began to glow at IR wavelengths. That dust echo was detected months after the event's initial optical emission. The blue emissions depict jets of plasma launched by the event. (Courtesy of the Science Communication Lab for DESY.)

On 1 October 2019, the IceCube Neutrino Observatory in Antarctica detected an exceptionally energetic 0.2 PeV neutrino. The Zwicky Transient Facility in California followed up seven hours later with wide-field observations of the sky at optical wavelengths. The facility observed optical emission in the 90% uncertainty region of the incoming neutrino.

After studying the large energy flux of the optical emission, its location within the reported uncertainty region of the sky where the high-energy neutrino came from, and some modeling results, researchers concluded that the two observations could be connected.[1] The optical emission was caused by a bright transient phenomenon known as a tidal disruption event (TDE) that had first been observed one year before the neutrino.

TDEs occur when stars get close enough to supermassive black holes to experience spaghettification—the stretching and compressing of an object into a long, thin strand that is caused by the black hole's extreme tidal forces. (See the article by Suvi Gezari, Physics Today, May 2014, page 37.)

Two theory papers proposed that neutrinos with energies above 100 TeV, like the 2019 sighting, could be produced in relativistic jets of plasma, which are composed of stellar debris that's flung outward after such an event.[2] Active galactic nuclei (AGNs) and other possible emitters of high-energy neutrinos have been debated in the literature before IceCube detected the first extragalactic ones in 2013 (see the article by Peter Mészáros, Physics Today, October 2018, page 36). But with only the one reported TDE–neutrino association from 2019, researchers haven't been able to conclusively establish TDEs as high-energy neutrino sources.

Now the Zwicky Transient Facility observed another TDE that was located within the uncertainty region of a neutrino detected by IceCube. With their colleagues, Simeon Reusch and Marek Kowalski (German Electron Synchrotron and Humboldt University of Berlin) estimated that the probability of a second such pairing happening by chance is 0.034%, lending more credence to TDEs as sources of high-energy neutrinos.[3]

Star light, star bright

The newly observed TDE is located in an AGN—the luminous, compact center of a galaxy. The galaxy in question is 4.4 billion light-years from Earth and has at its center a black hole with a mass of 31.5 million Suns. After a star got close enough to be ripped apart, its remains likely swirled around the black hole, accreted, and began shining brightly across many wavelengths.

That transient flare was first discovered at the Zwicky Transient Facility in May 2019 and reached peak luminosity in August 2019. The associated neutrino was detected by IceCube nine months later, by which time the flare's flux had decreased by about 30%. Such flares often last several months, although this one was still detectable as of June 2022.

A TDE isn't the only possible source of the flare. It could have come directly from the AGN. Because AGNs are far more numerous than TDEs, their emission is more common. And the first data of the flare suggested that it could have been a superluminous supernova—a stellar explosion with a luminosity that's at least 10 times as bright as a typical

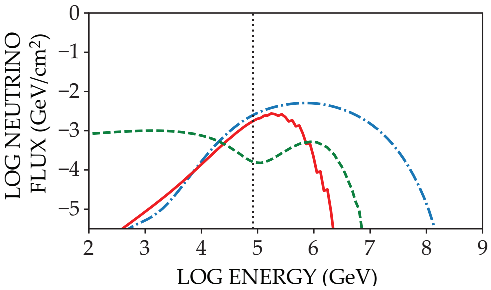

FIGURE 2. HIGH-ENERGY NEUTRINOS could be produced from various mechanisms associated with a tidal disruption event—the demise of a star by a supermassive black hole's tidal forces. The energy of one such neutrino (vertical dotted line), detected by the IceCube Neutrino Observatory in 2020, is consistent with all the modeled possibilities. It may have been generated from relativistic jets of plasma expelled from the event (blue dotted–dashed line), the collisional plasma inside the coronal region of an accretion disk composed of stellar debris (red solid line), or a subrelativistic wind of ejected material (green dashed line). (Adapted from ref. 3.)

supernova. To better establish whether a TDE was, in fact, the source of the optical emission, Reusch, Kowalski, and colleagues looked at measurements of the flare that spanned nearly the entire electromagnetic spectrum.

Some of the most useful evidence came from the eROSITA telescope, which is part of the Russian–German *Spektr-RG* satellite. The instrument scanned the sky location of the putative TDE four times. On the third scan in March 2021, after the peak luminosity of the flare had declined, it detected low-energy, or soft, x-ray emission, which would be quite uncommon for a superluminous supernova.

Sluggish IR

A second critical piece of evidence in support of the TDE came from mid-IR observations collected by the *NEOWISE* space telescope—NASA's reactivated *Wide-Field Infrared Survey Explorer* whose current mission is to identify and characterize near-Earth objects (see Physics Today, March 2015, page 19). The mid-IR observations showed a peak IR luminosity that curiously lagged the peak of the optical emission by a year.

"The time delay led us to the dust-echo interpretation," says Reusch. Figure 1 shows an artistic illustration of the AGN surrounded by a preexisting dust cloud; it heated up and started to glow as light traveled through it. The dust in the immediate vicinity of the disrupted star was destroyed by the TDE's radiation, which left only the far-flung dust surrounding the TDE.

In the dust-echo interpretation, some of the IR light emitted from the TDE was absorbed and reemitted by the surrounding dust. Light traveling directly along the line of sight to the TDE arrived at Earth first. IR light from the heated dust that was initially emitted perpendicular to the direct line of sight or from the far side of the system must travel farther and thus arrived months later than the optical emission.

Reusch, Kowalski, and their colleagues first modeled the combined IR, optical, and UV light coming from the TDE using a single blackbody as the radiation source. But the results were inconsistent with the spectral shape of the observations. The best fit, they found, came from a model composed of two blackbodies at different temperatures: one for the TDE emission and the other for the IR dust-echo emission.

From jets, the disk, or wind?

To better understand how the unusually long-lasting TDE may have produced high-energy neutrinos, the research team simulated three possible mechanisms. Besides relativistic jets, a TDE could also generate a disk of gaseous material accreted from the remains of a star. With sufficiently high accretion, collisional plasma in the coronal region of the disk may accelerate particles and produce neutrinos. Such an accretion disk could also launch a subrelativistic wind of ejected material that's energetic enough for generating neutrinos.

Figure 2 shows the predicted neutrino flux for each of the possible mechanisms as a function of energy. Any of the three mechanisms could reasonably generate a neutrino with the energy (vertical dotted line) observed by IceCube.

Other details of the TDE–neutrino association remain murky. For example, in their statistical analysis, IceCube researchers couldn't rule out the possibility that the neutrino may have formed from atmospheric processes on Earth. They concluded that the neutrino had a

59% probability of having an astrophysical origin.[3]

Multimessenger astrophysics

Detecting more TDEs and better establishing their relationship to high-energy neutrinos should be possible as early as next year. The Vera C. Rubin Observatory, previously named the Large Synoptic Survey Telescope, is currently being built in Chile. Once it sees first light, its wide-field Simonyi Survey Telescope will have the capability of photographing the entire sky every few nights.

If the TDE–neutrino association is true, TDEs would have to be extremely efficient particle accelerators. The energies of high-energy neutrinos are many orders of magnitude higher than can be reached in even the most impressive terrestrial particle accelerators, and they reach Earth largely unperturbed.

High-energy neutrinos, therefore, are a natural part of a multimessenger astrophysical laboratory. They can't be controlled or replicated as in a traditional lab experiment, but they can be used to study high-energy processes and test fundamental ideas about particle physics.

For example, some of the densest and most energetic conditions in the universe are found in supernovae. Because neutrinos are very light and only interact by the weak nuclear force, they can pass through the dense core of a supernova and probe the conditions there.

Neutrinos are also theoretically expected to be produced during neutron star mergers. None were seen after the 2017 binary neutron star merger in which gravitational waves and a gamma-ray burst were observed (see "The era of multimessenger astronomy begins," Physics Today online, 16 October 2017). Nevertheless, the hunt for them continues. And should any be detected, they may offer bits of information about the density of a neutron star merger and how energy is dissipated from it.

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A triatomic molecule is laser cooled and trapped

Molecules that stretch, bend, and rotate offer many new avenues for ultracold physics experiments. But they're also harder to control.

In March 2020, as the world was grappling with the implications of the COVID-19 pandemic, John Doyle and colleagues at Harvard University were faced with the bleak prospect of shutting down their experiments on ultracold atoms and molecules, perhaps indefinitely. So they turned their physics expertise to a rather different but more timely set of problems: Could N95 masks, in perilously short supply at the time, be decontaminated and reused?[1] And how could the risks of airborne disease transmission be most effectively mitigated in a laboratory or office setting?[2]

Through their work, they helped Harvard develop a plan to safely and quickly reopen its research labs—including their own, shown in figure 1. "By June 2020 we were working at 70% capacity," says Doyle, "and a couple months after that we were back to essentially 100%. Although we didn't have any visitors during the shutdown, we enjoyed the opportunity for quiet and concentration."

That opportunity has paid off. In one of a steady stream of papers published since the start of the pandemic, they've now demonstrated the laser cooling and magneto-optical trapping of calcium monohydroxide (CaOH), the first three-atom molecule to be so cooled and trapped.[3] The extension of ultracold techniques to larger molecules promises to make possible new experiments in quantum information, tests of fundamental physics, and more.

Will the cycle be unbroken?

Laser cooling and trapping of atoms is a decades-old technology that garnered the 1997 Nobel Prize (see Physics Today, December 1997, page 17). In its simplest form, it works by optical cycling: An atom repeatedly absorbs and emits photons as it hops between its ground and excited electronic states. Each absorbed photon imparts some momentum, which counters the atom's thermal kinetic energy, thereby slowing and cooling it.

The success of that method hinges on getting the atom to reliably return to its ground state. If there's some other low-lying state that it can relax into instead, researchers need to add another laser to repump the atom from that state; if the atom ever ends up in a so-called dark state that isn't repumped, the cooling cycle ends and the atom is lost from the experiment. The easiest atoms to laser cool are therefore those with the simplest energy-level structures, mostly alkali metals such as potassium and rubidium and alkaline earth metals such as calcium and strontium.

Extending ultracold methods from atoms to molecules is useful for a wide range of experiments. Some of those experiments are obvious, such as studying chemical reactions in the quantum regime (see the article by Debbie Jin and Jun Ye, Physics Today, May 2011, page 27); others are less so, such as searching for hypothetical supersymmetric particles that might endow the electron with a permanent electric dipole moment (see the article by Dave DeMille, Physics Today, December 2015, page 34).

But all the challenges of laser cooling atoms are compounded in molecules, which possess not only electronic quantum states but also quantized rotations and bond vibrations. The veritable continuum of low-lying states would, in the general case, require many dozens of repumping lasers to keep under control.

Because of the difficulty of cooling molecules directly, most ultracold-molecule researchers build their molecules from atoms that are already cooled. Although that approach works well, it yields exotic, weakly bound molecules such as KRb (see Physics Today, February 2020, page 12) and Sr_2 (see Physics Today, October 2019, page 18) that are essentially unknown outside of ultracold research.