Pushing the limits of discovery

Be it neutrinos, ultra-high-energy photons or gravitational waves, new cosmic messengers have expanded the available discovery space of astronomy by exploring previously inaccessible astrophysical environments.

The neutrino, an elusive elementary particle with a rest mass so small that it can effectively be considered zero, is the perfect messenger from afar. Because they only interact with matter through the weak interaction and gravity (also weak, given their vanishingly small mass), neutrinos are able to escape most environments unscathed and unchanged, hence delivering pristine information on a number of (astro)physical processes. That is the theory of course, because in practice and exactly due to their elusiveness, detecting these neutrinos is no easy feat.

While the direct detection of a (man-made) neutrino through the beta capture process occurred in 1956, it was not until 1968 that the first extraterrestrial neutrinos, from the Sun, were detected by the Homestake experiment, marking the start of neutrino astronomy. Two more decades passed before a fortuitous supernova in our nearby Large Magellanic Cloud led to the detection of neutrinos from further away in our cosmic neighbourhood. The neutrino detector Kamiokande-II measured eleven neutrinos from the supernova SN 1987A in February 1987. This discovery, which together with the detection of solar neutrinos led to a Nobel Prize for Masatoshi Koshiba and Raymond Davis Jr, further established the field of neutrino astronomy.

Fast-forward to today and the field is in full bloom. There are now multiple neutrino experiments around the globe. Whether using ice, water, heavy water or even chlorine, the principle of all neutrino detectors is the same: put a large enough volume of a homogeneous medium in the path of neutrinos and one of them is bound to interact. The most sensitive and high-resolution detector currently in operation, the IceCube Neutrino Observatory in Antarctica, has been detecting cosmic neutrinos since the early 2010s.

Despite routine detections of cosmic neutrinos, understanding and studying their origins has not been straightforward. On top of the very fundamental issues of separating signal from noise, and solar neutrinos from other cosmic neutrinos, the poor angular localization of neutrino detectors (at best ~0.7° for the highest energies for IceCube) makes it extremely difficult to pinpoint the direction on the sky from which a specific event is coming. In 2017, the coincidence of a neutrino event with a flaring blazar was a big step forward. It confirmed that active galactic nuclei are potent particle accelerators and one of the sources of high-energy cosmic neutrinos (see Elena Pian's News & Views).

In this issue of *Nature Astronomy*, Robert Stein and collaborators report the association of a high-energy neutrino event with a different type of astrophysical source: a tidal disruption event, when a star is pulled apart during its infall towards a supermassive black hole. In a companion paper, Walter Winter and Cecilia Lunardini present an astrophysical model explaining the observations. As for the blazar association before it, the additional information carried by the IceCube-detected neutrino event provides valuable insights into tidal disruption events (see a discussion by Kimitake Hayasaki).

Neutrinos are not the only tool currently used for pushing the limits of astrophysical discovery. Ultra-high-energy astrophysics is also enjoying a productive era, with multiple facilities now online to investigate this as yet scarcely explored part of the electromagnetic spectrum. The detection of the Crab nebula in the very-high-energy gamma rays by the Whipple telescope in 1989 led to a number of concurrent and subsequent experiments (including HESS, MAGIC and VERITAS) looking to expand our understanding of the very-high-energy gamma-ray sky.

In this issue, we publish two new sets of observations pushing the limits of very-high-energy gamma-ray astronomy in the TeV range. The High-Altitude Water Cherenkov Observatory and the Tibet air shower array report the detection of the Cygnus cocoon and the supernova remnant G106.3+2.7, respectively. Both studies constrain the astrophysical processes leading to the acceleration of cosmic-ray particles to PeV energies in two different and unexpected astrophysical environments.

There are interesting parallels to be drawn between neutrino and very-high-energy gamma-ray astronomy. Both probe highly energetic astrophysical processes that might otherwise be hidden from conventional astronomical observations. Furthermore, given the challenges linked to the technology required for their detection, both probes have only recently entered an era of reliable detections of multiple events. While high-energy gamma-ray astronomy may have a head start — it is after all an extension of the electromagnetic spectrum, which astronomers have been studying for a very long time — both fields are set to grow exponentially over the coming years. The next milestone for high-energy gamma-ray astronomy will be the commissioning of the Cherenkov Telescope Array (first operations are expected to commence next year), which will afford unprecedented sensitivity and localization capabilities up to energies of 300 TeV and will tackle a number of fundamental physical and astrophysical questions (see a Meeting Report from the first Cherenkov Telescope Array symposium in 2019). Concerning neutrinos, in addition to upgrading the capabilities of IceCube, several next-generation neutrino detectors are planned (including KM3NeT and the Pacific Ocean Neutrino Experiment).

The observational arsenal of astronomers keeps increasing and every additional way of looking at the night sky leads to an expanded discovery space, a deeper understanding of long-studied astrophysical phenomena and in some cases the discovery of completely new phenomena. Most tantalizingly, for both neutrinos and very-high-energy gamma-rays, these observational probes straddle the (admittedly fuzzy) division between physics and astrophysics. The potential of cross-pollination and serendipitous discoveries should motivate both communities to keep pushing those limits further. ❐

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