

Black holes associated with cosmic neutrino flares

Astrophysical neutrinos could originate from blazars, but their modelling is challenging. Instead, the source of cosmic neutrinos could be a special yet unidentified class in which jets burrow through stellar material and produce neutrinos.

Francis Halzen and Ali Kheirandish

High-energy neutrinos originate from the interaction of accelerated cosmic rays with radiation, gas or molecular clouds of sufficient density to produce pions and kaons that further decay into neutrinos. Because cosmic rays are charged, their arrival directions at Earth are scrambled and, more than a hundred years after their discovery, the origin of cosmic rays is still unknown. However, this problem does not apply to neutrinos, which point back to their source. Although IceCube detected an extragalactic flux of neutrinos, only neutrino IC170922 with an energy of 290 TeV could be associated with a source by taking advantage of temporally coincident multimessenger observations that identified the active galactic nucleus, TXS 05060+056, as its origin¹. With this information, a search in the previously recorded data set revealed a further 13 neutrinos detected in 2014–15. This cosmic neutrino flare lasted over 110 days, which dominated the flux of the high-energy neutrinos from the direction of TXS 0506+056 over the 9.5 years of IceCube observations².

This leaves the IC170922 event as a second subdominant flare, for which a wealth of information on the source is available from the real-time multimessenger campaign. However, such data are scarce for the earlier neutrino flare. The neutrino alert issued by IceCube in 2017 coincided with the peak emission of a gamma flare that increased the flux by a factor of seven over the steady flux observed by the Fermi satellite. Additionally, the MAGIC telescope established the source of the gamma-ray enhancement as a relatively rare TeV blazar (Fig. 1), but no such enhancements were present for the neutrino flare in 2014.

Blazar modelling of both cosmic neutrino flares has so far been unsuccessful because conventional models, in which the entire multi-wavelength emission is attributed to a single dominant emission region in the jet, fail to describe the simultaneous emission

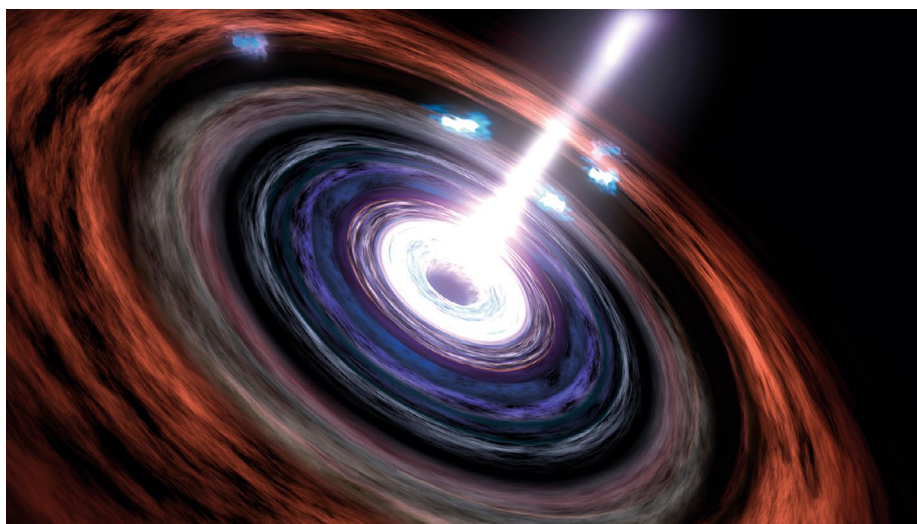


Fig. 1 | Blazar shoots neutrinos and gamma rays to Earth. Blazars are a type of active galaxy with two jets, where one jet is pointing towards Earth. In this artistic rendering of a blazar, the active galactic nucleus powers beams of both neutrinos and gamma rays. Those signals are detectable by the IceCube Neutrino Observatory in Antarctica or by other space- or ground-based telescopes. Credit: Stocktrek Images, Inc. / Alamy Stock Photo

of neutrinos and gamma rays during the flares of TXS 05060+056. Blazar models at best explain the single neutrino in 2017 by invoking a fortuitous fluctuation³ and fail to accommodate the 2014 burst. This calls a conventional blazar origin of the two cosmic neutrino flares from TXS 05060+056 into question.

The answer to this puzzle could be a new subclass of high-energy gamma-ray sources that produce the high-energy cosmic neutrinos and cosmic rays observed⁴. Such a scenario is supported by two recent observations. First, a high-resolution radio image of the source, TXS 0506+056, provided evidence for the merger of two galaxies in the blazar⁵. Second, the high intensity of the neutrino flux observed by IceCube below 100 TeV relative to the Fermi data might indicate that the neutrinos

originate in hidden sources that are more efficient emitters of neutrinos than gamma rays⁶, with the electromagnetic radiation accompanying the neutrinos below the detection threshold of the Fermi satellite. In fact, the data challenge the identification of the source as a blazar and instead point to a unique class of sources dominating the high-energy Universe, as we will argue in the following.

If blazars in general produced neutrinos at similar levels to TXS 0506+056, the total diffuse flux observed by IceCube would be enhanced by almost two orders of magnitude. The observed cosmic neutrino flux can be accommodated by a subclass of sources at the level of 5% of the blazars observed by Fermi, bursting once in ten years similar to TXS 0506+056 (ref. ⁴). Additionally, the source outshines

nearby blazars by a factor of ten — despite the fact that it is more distant. A simple energy-balance calculation shows that a source producing 13 neutrinos in three months requires a large target density that is inevitably opaque to high-energy gamma rays. Therefore, we argue that TXS 0506+056 belongs to a special subclass of sources with the following characteristics: the source must accelerate protons and have a sufficient target density to enable the production of very high-energy gamma rays and neutrinos.

The argument that cosmic rays must be highly efficient in producing neutrinos is strengthened by the observation that the energy content of neutrinos and very-high-energy cosmic rays throughout the Universe is similar. A source with an opacity that exceeds a value of 0.4 (ref. ⁴) results in a gamma-ray cascade down to energies in the extragalactic background light range. Most of the gamma-ray energies fall below the detection threshold of the Fermi satellite by the time they reach Earth. For this reason, the 2014–2015 burst is not accompanied by a large gamma-ray flare, which is consistent with observations. Unfortunately, in the absence of temporally coincident multimessenger data in 2014 and no telescope presently exploiting the MeV energy range, the hypothesis that a special subclass of sources that deposit their energy below the Fermi threshold are responsible for the neutrino flares is hard to confirm.

But what could the nature of such a special class of efficient sources be? One straightforward explanation could be a subclass of blazars selected by redshift evolution: the neutrino flares could have been produced by proton accelerators that were active in the past. This would accommodate the large redshift of TXS 0506+056 (ref. ⁷) because it would then be the closest among a set of sources that only accelerated cosmic rays at large redshifts.

Another possibility is that the source must have a large target density in photons or protons in order to produce neutrinos at the high flux level observed from TXS 0506+056. In order to explain the 2014–2015 observation, the required target density points towards a source in the vicinity of a black hole⁴. Follow-up studies of TXS 0506+056 with the VLBA radio array have shown the presence of a warped jet or potentially a collision of two jets^{5,8}. The interaction of the jetted material could account for the abundant neutrino emission. The VLBA observation also reveals that the neutrino burst occurs at the peak of enhanced radio emission at

15 GHz, which started five years ago. In fact, a strong brightening of the core of the galaxy in radio emission accompanies both episodes of neutrino activity observed from TXS 0506+56. This observation supports the hypothesis of high-energy neutrino production close to black holes.

The above discussion explains why previous attempts by IceCube and others to find correlations between the point of origin of high-energy neutrinos and all observed Fermi blazars were unsuccessful, because the IceCube data may not have the statistical power to identify a correlation without prior identification of the subclass of sources.

Recently, a correlation between the blazar PKS 1502+106 and a 300-TeV neutrino alert, IC-190730 (ref. ⁹), was reported. Observations from the Owens Valley Radio Observatory¹⁰ suggest that this neutrino coincides with the peak flux density of a five-year long flare at 15 GHz (ref. ¹¹). This agrees with the similar long-term radio outburst seen from TXS 0506+056. Because radio bursts are believed to be correlated with mergers of supermassive black holes¹², these long-time radio bursts might be a sign of such a merger. The material involved in the mergers of black holes provides an optically thick environment enabling neutrino production. A cursory review of the literature on the production of neutrinos in galaxy mergers is sufficient to conclude that it can indeed accommodate the observations of both sources discussed above and the diffuse flux of cosmic neutrinos; see for example, refs. ^{13–15}.

There is another — possibly related — development associated with the search for steady neutrino sources that recently delivered a new time-integrated neutrino sky map covering ten years of IceCube data¹⁶. Evidence at the 3σ level suggests that this neutrino sky map might no longer be isotropic. The anisotropy results from four sources — TXS 0506+056 among them — that emerge at the 4σ level. The strongest of these sources is the nearby galaxy NGC 1068 (also known as Messier 77) with starburst activity. Observations suggest the presence of shocks near the core of the galaxy, and for molecular clouds with densities exceeding 10^5 cm^{-3} . Similar to TXS 0506+056, a merger of the black hole in the galaxy's centre with either a star-forming region or a satellite galaxy is observed¹⁷. Therefore, the increased neutrino emission, as emerging from the neutrino sky map, may be caused by a merger with sufficient mass.

The assumption that the evolution of most radio galaxies involves mergers^{12,18} supports the proposal of redshift evolution

selecting a special class of sources to account for the two cosmic neutrino flares observed by the IceCube collaboration. In this scenario, rapid changes in jet ejection direction and instabilities in the accretion disk provide a possible production mechanism for the cosmic neutrino flares. In this context, previous studies of the neutrino emission from radio galaxies are also relevant as they require a high density close to the source^{19,20}. Furthermore, far-infrared observations support the argument that the central activity of the galaxies, such as starburst activity, is fuelled by the concentration of matter that may be preceded by a merger²¹.

In a major merger scenario, when two galaxies with supermassive black holes at their centres merge, a spin-flip of the leading jet is expected to occur owing to the spin-orbit precession and energy dissipation from gravitational radiation^{12,22}. A burst of neutrinos may result from the jet sweeping through the dense material that accumulates between the merging black holes²³.

The developments discussed here underscore the importance of electromagnetic measurements other than those of gamma rays, from radio to MeV wavelengths. They also suggest redirecting the search for the origin of cosmic rays to the special class of sources, such as a certain subclass of blazars or merged radio galaxies, rather than trying to find correlations with the broad classes of blazars. □

Francis Halzen ^{1,2} and Ali Kheirandish ^{1,2}

¹Department of Physics, University of Wisconsin–Madison, Madison, WI, USA. ²Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin–Madison, Madison, WI, USA.
e-mail: francis.halzen@icecube.wisc.edu;
ali.kheirandish@icecube.wisc.edu

Published online: 6 April 2020
<https://doi.org/10.1038/s41567-020-0864-2>

References

1. The IceCube Collaboration. *Science* **361**, eaat1378 (2018).
2. The IceCube Collaboration. *Science* **361**, 147–151 (2018).
3. Strotjohann, N. L., Kowalski, M. & Frackowiak, A. *Astron. Astrophys.* **622**, L9 (2019).
4. Halzen, F., Kheirandish, A., Weisgarber, T. & Wakely, S. P. *Astrophys. J.* **874**, L9 (2019).
5. Britzen, S. et al. *Astron. Astrophys.* **630**, A103 (2019).
6. Murase, K., Guetta, D. & Ahlers, M. *Phys. Rev. Lett.* **116**, 071101 (2016).
7. Neronov, A. & Semikoz, D. V. Preprint at: <https://arxiv.org/abs/1811.06356> (2018).
8. Kun, E., Biermann, P. L. & Gergely, L. A. *Mon. Not. R. Astron. Soc.* **483**, L42–L46 (2019).
9. Lipunov, V. et al. *The Astronomer's Telegram* <http://www.astronomersteletgram.org/?read=12971> (2019).
10. Kiehlmann, S., Hovatta, T., Kadler, M., Max-Moerbeck, W. & Readhead, A. C. S. *The Astronomer's Telegram* <http://www.astronomersteletgram.org/?read=12996> (2019).
11. Karamanavis, V. et al. *Astron. Astrophys.* **586**, A60 (2016).
12. Gergely, L. A. & Biermann, P. L. *Astrophys. J.* **697**, 1621–1633 (2009).

13. Kashiwama, K. & Mészáros, P. *Astrophys. J.* **790**, L14 (2014).
14. Yuan, C., Mészáros, P., Murase, K. & Jeong, D. *Astrophys. J.* **857**, 50 (2018).
15. Yuan, C., Murase, K. & Mészáros, P. *Astrophys. J.* **878**, 76 (2019).
16. The IceCube Collaboration. *Phys. Rev. Lett.* **124**, 051103 (2020).
17. García-Burillo, S. et al. *Astron. Astrophys.* **567**, A125 (2014).
18. Rottmann, H. *Jet-Reorientation in X-shaped Radio Galaxies*. Ph.D. thesis, Univ. of Bonn (2001).
19. Becker Tjus, J., Eichmann, B., Halzen, F., Kheirandish, A. & Saba, S. M. *Phys. Rev. D* **89**, 123005 (2014).
20. Hooper, D. J. *Cosmol. Astropart. Phys.* <https://doi.org/10.1088/1475-7516/2016/09/002> (2016).
21. Sanders, D. B. & Mirabel, I. F. *Ann. Rev. Astron. Astrophys.* **34**, 749 (1996).
22. Biermann, P. L. et al. *Nucl. Phys. B* **190**, 61–78 (2009).
23. Gopal-Krishna, Wiita, P. J. & Joshi, S. *Mon. Not. R. Astron. Soc.* **380**, 703–711 (2007).

Acknowledgements

We thank P.L. Biermann, M. Böttcher, S. Heinz, and J. Gallagher for fruitful discussions. This work was supported in part by the US National Science Foundation under grants PLR-1600823 and PHY-1607644 and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.