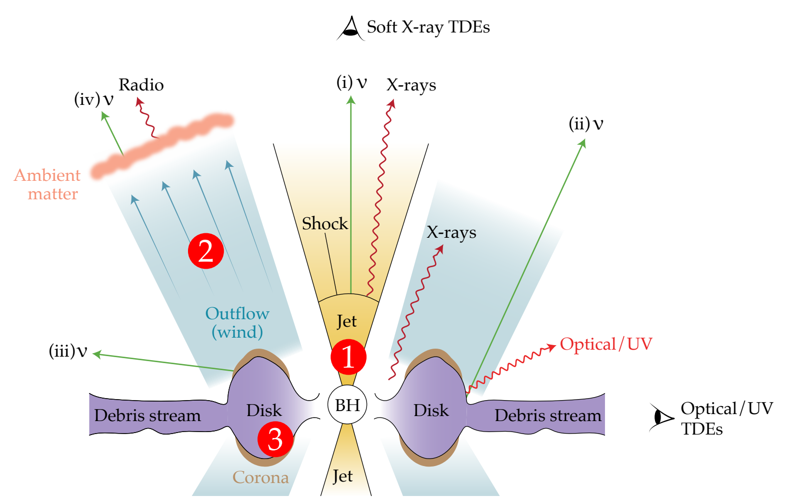
Soft X-ray TDEs
Radio
(iv) ν
(i) ν
X-rays
(ii) ν
Ambient matter
Shock
X-rays
2
Outflow (wind)
Jet
(iii) ν
1
Optical/UV
BH
Debris stream
Disk
Disk
Debris stream
Optical/UV TDEs
3
Corona
Jet

rate increases as the density of supplied photons increases, the production efficiency decreases as the size of the plasma shell increases. The balance of these two explains the ~150 day delay between the neutrino detection and the observed optical/UV peak of the TDE.

However, there are some shortcomings in explaining the TDE neutrino via a relativistic jet model. Around 100 TDE candidates have so far been observed, of which only three are clearly jetted TDEs[10]. Furthermore, no high-energy gamma-ray and hard X-ray emissions[5] have been observed from AT2019dsg, which would be a clear signature for the production of neutrinos in a relativistic jet, and the detected radio emission from AT2019dsg is too weak for a relativistic jet[8]. An off-axis[11] or hidden[12] jet model could, however, explain some of these inconsistencies. There are a few alternative models to produce sub-PeV neutrinos from TDEs: an accretion disk, disk corona and wind/outflow[13,12] (see also Fig. 1). These are mainly promising for non-jetted TDEs, for which the event rate is much higher than for the jetted-TDE case. For example, the sub-PeV neutrinos could be emitted from a super-Eddington magnetically arrested disk (MAD) or a radiatively inefficient accretion flow (RIAF) in the TDE context[13]. Interestingly, the disk's protons would accelerate by the second-order Fermi acceleration via disk turbulence, which is different from the relativistic jet model, for which the first-order Fermi acceleration via the shock works. Moreover, high-energy (TeV-scale) gamma-rays are not emitted by efficient pair production in the RIAF model, which would explain the non-detection of AT2019dsg at these highest energies. The main challenge for future multi-messenger studies of TDEs will be to explore whether TDE neutrinos originate from a relativistic jet, accretion disk, disk corona, disk wind/outflow, or other sources. Clues to their production site would come from identifying the acceleration mechanism, cooling process, hadronuclear and photohadronic interactions, and cascading processes, which differ depending on the given neutrino emitter model[12].

The IceCube-191001A-AT2019dsg association represents the first step in the study of high-energy particle emission from TDEs. Ongoing and future all-sky-survey telescopes (such as SRG/e-ROSITA, the Vera C. Rubin Observatory Legacy Survey of Space of Time and the Einstein Probe) will increase the TDE detection rate up to the order of thousands per year[10]. In addition, the next-generation IceCube will offer higher sensitivity and better angular resolution[14], further improving the localization of astrophysical neutrinos and subsequent association with TDEs or other astrophysical sources. The robust detection of TDE neutrinos will elucidate not only the observed diversity of TDEs but may also help constrain the as-yet-unknown neutrino mass and lifetime. It will be interesting to see if there is any correlation between the electromagnetic radiation variability and the high-energy neutrino emission. The IceCube-191001A-AT2019dsg association marks the beginning of multi-messenger observations for TDEs. ❐

Kimitake Hayasaki ✉
Department of Astronomy and Space Science, Chungbuk National University, Cheongju, Republic of Korea.
✉*e-mail: kimi@cbnu.ac.kr*

Published online: 22 February 2021
https://doi.org/10.1038/s41550-021-01309-z

References

1. Weinberg, S. *Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity* (Wiley, 1972).
2. Alpher, R. A., Follin, J. W. Jr. & Herman, R. C. *Phys. Rev.* **92**, 1347 (1953).
3. The IceCube Collaboration. et al. *Science* **361**, eaat1378 (2018).
4. Koshiba, M. *Phys. Rep.* **220**, 229–381 (1992).
5. Stein, R. et al. *Nat. Astron.* https://doi.org/10.1038/s41550-020-01295-8 (2021).
6. Rees, M. J. *Nature* **333**, 523–528 (1988).
7. van Velzen, S., Holoien, T. W.-S., Onori, F., Hung, T. & Arcavi, I. *Space Sci. Rev.* **216**, 124 (2020).
8. Alexander, K. D., van Velzen, S., Horesh, A. & Zauderer, B. A. *Space Sci. Rev.* **216**, 81 (2020).
9. Winter, W. & Lunardini, C. *Nat. Astron.* https://doi.org/10.1038/s41550-021-01305-3 (2021).
10. Stone, N. C. et al. *Space Sci. Rev.* **216**, 35 (2020).
11. Liu, R.-Y., Xi, S.-Q. & Wang, X.-Y. *Phys. Rev. D.* **102**, 083028 (2020).
12. Murase, K., Kimura, S. S., Zhang, B. T., Oikonomou, F. & Petropoulou, M. *Astrophys. J.* **902**, 108 (2020).
13. Hayasaki, K. & Yamazaki, R. *Astrophys. J.* **886**, 114 (2019).
14. Aartsen, M. G. et al. Preprint at https://arxiv.org/abs/1911.02561 (2019).
15. Dai, L., McKinney, J. C., Roth, N., Ramirez-Ruiz, E. & Miller, M. C. *Astrophys. J. Lett.* **859**, L20 (2018).

Competing interests

The author declares no competing interests.