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Choked jets in expanding envelope as the origin of the neutrino emission associated with Tidal Disruption Event

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Three tidal disruption event (TDE) candidates (AT2019dsg, AT2019fdr, AT2019aalc) have been found to be coincident with high-energy astrophysical neutrinos in multimessenger follow-ups. Recent studies suggest the presence of a quasi-spherical, optically thick envelope around the supermassive black holes in TDEs, resulted from stellar debris after the disruption. The envelope may expand outwardly with a velocity of $\sim 10^4$ kms^{-1}, as indicated by the emission line widths. We study whether the neutrino signal can be explained by choked relativistic jets inside the expanding envelope. While powerful jets, such as that in Swift J1644+57, can successfully break out from the envelope, those with relatively weak power could be choked by the envelope. Choked jets can still accelerate cosmic rays and produce high-energy neutrinos via interaction with the thermal photons in the envelope. We explore the parameter space of the jets that can produce detectable neutrino flux while being choked in the expanding envelope. We find that the cumulative neutrino numbers of AT2019fdr and AT2019aalc are consistent with the expected range imposed by observations, while the allowed parameter space for AT2019dsg is small. The neutrino time delay relative to the optical peak time of TDEs can be explained as the jet propagation time in the envelope before being choked. The discovery of TDE-associated neutrino events may suggest that jets might have been commonly formed in TDEs, as expected from super-Eddington accretion, but most of them are too weak to break out from the expanding envelopes.

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1. Model description

In the process of Tidal Disruption Events (TDEs), approximately half of the disrupted star's mass remains gravitationally bound, while the remaining materials are expelled outwardly due to radiation pressure (with a density $\rho \propto r^{-3}$) or through a disk wind (with a density $\rho \propto r^{-2}$). Both of these mechanisms give rise to the formation of thermal and optically dense expanding outflows surrounding the supermassive black hole, commonly referred to as the envelope of TDEs. If there are jets present within this envelope, protons accelerated by internal shocks can interact with thermal photons inside the envelope, producing the emission of observable neutrinos (see Figure 1). The delay between neutrino triggers and optical peaks can be explained by the jet propagation in the envelope.

For a typical solar mass envelope, the velocity of the jet head is Newtonian $\beta_\mathrm{h} - \beta_\mathrm{env,h} \approx 0.05$. Gottlieb & Nakar (2022) found that in the Newtonian case, there is a simple analytic breakout criterion for jets [1]

$$E_\mathrm{j,iso} > \tilde{E}_\mathrm{a}(n) \frac{(5-n)^{4-n}}{N_\mathrm{E}^5(n)} E_\mathrm{env,kin} \theta_\mathrm{j,0}^2, \tag{1}$$

$$> \begin{cases} 299 E_\mathrm{env,kin} \theta_\mathrm{j,0}^2 (\rho \propto r^{-2}) \\ 698 E_\mathrm{env,kin} \theta_\mathrm{j,0}^2 (\rho \propto r^{-3}) \end{cases}, \tag{2}$$

where $\tilde{E}_\mathrm{a}(n)$ and $N_\mathrm{E}(n)$ are numerical factors calibrated by simulations, $\theta_\mathrm{j,0}$ is the initial half open angle of the jet, $E_\mathrm{j,iso} = \int L_\mathrm{j,iso} dt$ and $E_\mathrm{env,kin}$ is the total isotropic equivalent energy of jets and the kinetic energy of the envelope, respectively.

To calculate the break-out time of jets and neutrino flux in the three TDEs, the kinetic energy of the envelopes of each TDE are required. We take the velocity of the envelope as v$\sim 10^4 \mathrm{kms}^{-1}$ for three TDEs and suggest two approaches to estimate the envelope mass. The first approach

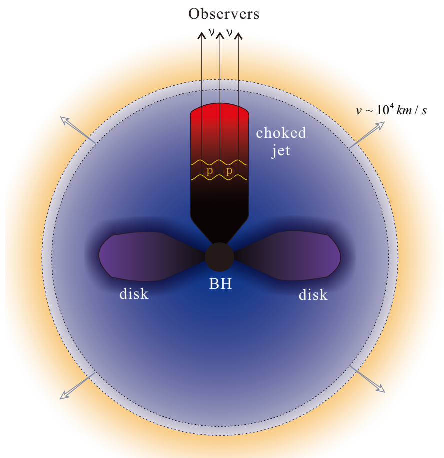

Figure 1: The schematic picture of a choked TDE jet in an expanding envelope. A quasi-spherical envelope surrounds the BH. Internal shocks (yellow wavy lines) occurred within the jet accelerate cosmic-ray protons, which produce neutrinos observed by us.

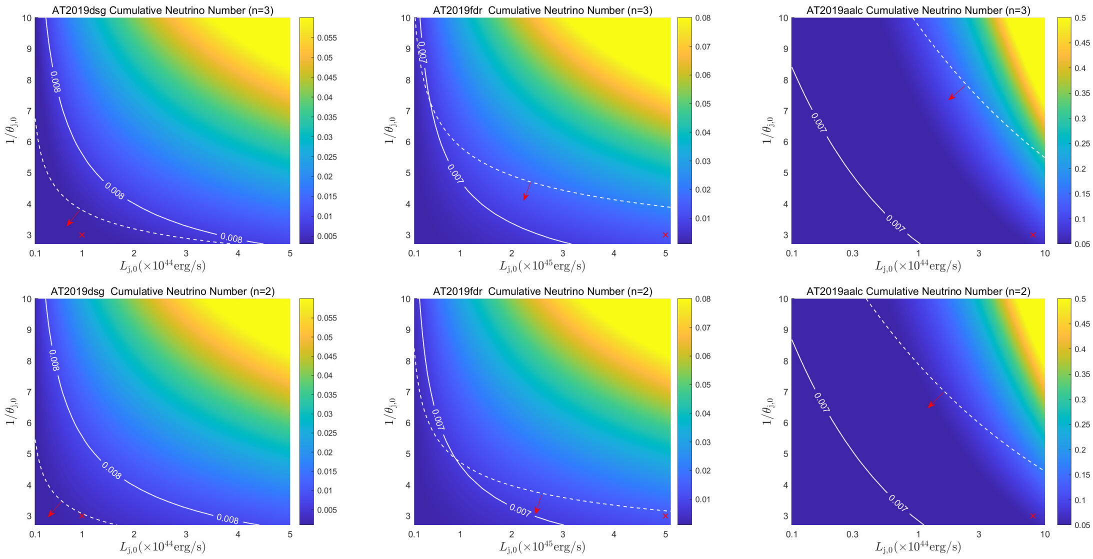

Figure 2: . The accumulative neutrino numbers (the color map) as a function of the jet luminosity and bulk Lorentz factor assuming envelope masses of three TDEs given in case A. The white solid lines represent the parameter values corresponding to the minimally required neutrino numbers, which are $N_\nu = 0.008$ for AT2019dsg and $N_\nu = 0.007$ for AT2019fdr and AT2019aalc. The white dashed line represents the critical parameter values for jets being choked and the direction of the arrow means that the permitted parameter space for choked jets is below this line. In case A, neutrinos from choked jets are allowed for AT 2019fdr and AT 2019aalc.

uses the photosphere radius given by $R_{\rm ph} \simeq 10^{15}{\rm cm}\,(M_{\rm env}/0.5M_\odot)^{1/2}$ for a radiation-pressure supported envelope or a steady state wind outflow [2], and the other uses the bolometric energy $E_{\rm bol} \approx L_{\rm acc,max}\tau \propto M_\star$ [3]. We define the above two cases as Case A and Case B, respectively. As shown in Figure 2&3, AT 2019dsg and AT 2019aalc have permitted parameter space in case A and case B while AT 2019dsg is only permitted in case B.

2. Conclusion and discussion

We have proposed that the neutrino emission associated with three non-jetted TDEs can be explained by the choked jet model, where relativistic jets are choked inside the quasi-spherical, optically thick envelope formed from stellar debris of TDEs. From an observational perspective, the presence of such an envelope provides a solution to the puzzle that the temperatures (few 10^4K) found in optically discovered TDEs are significantly lower than the predicted thermal temperature ($> 10^5$K) of the accretion disk. While powerful jets, such as that in Swift J1644+57, can break out from the envelope, jets with lower power would be choked inside the envelope.

Shocks within choked jets accelerate cosmic-ray protons, which subsequently interact with thermal photons inside the envelope via $p\gamma$ interactions, leading to the generation of high-energy neutrinos. The energy of neutrinos produced by choked jets is typically around hundreds of TeV, consistent with the measured energy of three neutrino events. The notable time delay of several hundred days between neutrino arrival time and TDE optical peaks can be explained as the

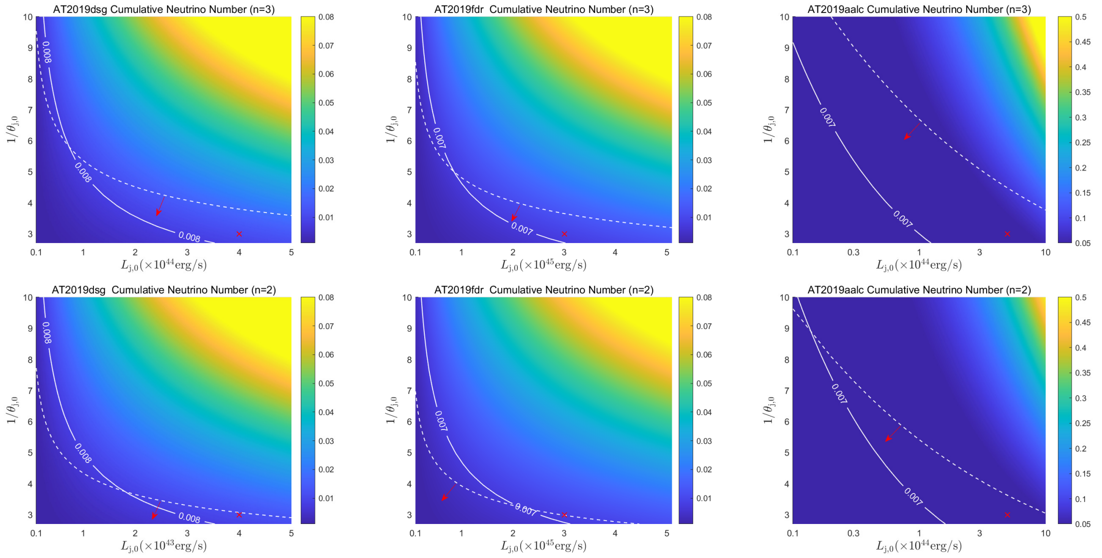

Figure 3: Same as Figure 2, but using the envelope masses of three TDEs given in Case B. In case B, neutrinos from choked jets are allowed for three TDEs.

propagation time of the jets before being choked in the envelope. The cumulative neutrino numbers in our model are consistent with the expected range for individual TDEs and can reach N_ν= 0.2 in the case of AT2019aalc. One important advantage of the choked jet model is that the neutrino flux is magnified by the beaming effect due to the relativistic bulk motion.

Noting that AT 2019fdr and AT 2019aalc are not common TDEs because they are more luminous (> 10^{44} erg/s) and long-lasting (>700days) [4, 5], the jet luminosity and neutrino emission of these two TDEs could be larger than common TDEs. Neutrinos from choked jets in common TDEs are calculated in Wang & Liu (2016), which will not overproduce the neutrino background detected by ICECUBE [6].

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