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Tidal disruption jets of supermassive black holes as hidden sources of cosmic rays: Explaining the IceCube TeV-PeV neutrinos

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Cosmic ray interactions that produce high-energy neutrinos also inevitably generate high-energy gamma rays, which finally contribute to the diffuse high-energy gamma-ray background after they escape the sources. It was recently found that the high flux of neutrinos at ∼30 TeV detected by IceCube lead to a cumulative gamma-ray flux exceeding the Fermi isotropic gamma-ray background at 10–100 GeV, implying that the neutrinos are produced by hidden sources of cosmic rays, where GeV-TeV gamma rays are not transparent. Here we suggest that relativistic jets in tidal disruption events (TDEs) of supermassive black holes are such hidden sources. We consider the jet propagation in an extended, optically thick envelope around the black hole, which results from the ejected material during the disruption. While powerful jets can break free from the envelope, less powerful jets would be choked inside the envelope. The jets accelerate cosmic rays through internal shocks or reverse shocks and further produce neutrinos via interaction with the surrounding dense photons. All three TDE jets discovered so far are not detected by Fermi/LAT, suggesting that GeV-TeV gamma rays are absorbed in these jets. The cumulative neutrino flux from TDE jets can account for the neutrino flux observed by IceCube at PeV energies and may also account for the higher flux at ∼30 TeV if less powerful, choked jets are present in the majority of TDEs.

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I. INTRODUCTION

Extraterrestrial neutrinos have been detected in various analyses and found to be consistent with an isotropic flux of neutrinos that is expected from extragalactic astrophysical source populations [1]. The source of the IceCube neutrinos is still controversial. The proposed astrophysical sources include galaxies with intense star formation [2], jets and/or cores of active galactic nuclei (AGNs) [3], AGN giant flares [4], gamma-ray bursts [5,6], etc. The astrophysical high-energy neutrinos are generated in the decay of charged pions produced in inelastic hadronuclear (pp) and/or photohadronic ($p\gamma$) processes of cosmic rays (CRs), both of which generate high-energy gamma rays from the decay neutral pions. As the recent combined likelihood analysis of IceCube gives an all-flavor neutrino flux of $\sim 10^{-7}$ GeV cm^{-2} s^{-1} sr^{-1} at about 30 TeV [1], it is argued that the cumulative gamma-ray flux associated with the neutrino emission is in tension with the Fermi diffuse extragalactic gamma-ray background (EGB) at 10–100 GeV [7,8]. The case gets stronger as new studies of the EGB composition at energies above 50 GeV find a dominant contribution from blazars, leaving only a ∼14% residual component for all other sources classes [9]. Motivated by this, it is argued that IceCube neutrinos may come from CR accelerators that are hidden in GeV-TeV gamma rays, so they would not overshoot the diffuse EGB [8,10]. Choked jets in collapsing massive stars [11,12] and cores of active galactic nuclei have been suggested to be such hidden sources [6,8]. Here we propose a new hidden source model, i.e., relativistic jets in tidal disruption events (TDEs) of supermassive black holes (SMBHs).

In TDEs, a star is torn apart by gravitational tidal forces of a SMBH, leading to a transient accretion disk which produces a bright panchromatic flare [13]. There are growing number of candidate TDEs that have been discovered in x-ray, ultraviolet, and optical surveys (see [14] for a review). Three TDE candidates have been also detected in nonthermal x-ray and radio emission, i.e., Swift J1644 + 57, J2058 + 05, and J1112-8238 [15–19]. The nonthermal x-ray and radio emissions are thought to be produced by relativistic jets, in which shocks occur and accelerate nonthermal electrons. These shocks may also accelerate CR protons [20–22], which can produce neutrinos via interaction with x-ray photons. Recent studies suggest the presence of an extended, quasispherical, optically thick envelope around the SMBH in TDEs [23–26]. Here we suggest that CRs accelerated by jets as they are propagating in the envelope can also produce neutrinos via interaction with surrounding dense photons. Fermi and VERITAS observations of Swift J1644 + 57 have failed to detect high-energy emission above 100 MeV during the x-ray flare [15]. Analysis of the Fermi/LAT data of the other two TDE jet flares also find no high-energy emission [27], suggesting that TDE jet flares are hidden sources in GeV-TeV gamma rays.

II. JET PROPAGATION AND DISSIPATION

The environment surrounding the TDE jet, after its launch, may be complex and needs detailed numerical works. It is thought that an extended, quasispherical, optically thick gas is present around the SMBH after disruption [23–26,28]. The presence of the gas can solve the puzzle that the temperatures (few 10^4 K) found in optically discovered TDEs are significantly lower than the predicted thermal temperature ($> 10^5$ K) of the accretion disk [29]. The gas at large radii can absorb UV photons produced by the inner accretion disk and re-emits it at lower temperatures of a few times 10^4 K. This reprocessing region may be due to the formation of a radiation-dominated envelope around the SMBH [23–25], or a super-Eddington wind outflow [28]. We invoke the envelope scenario to describe the density profile of the gas environment for the purpose of calculating the dynamics of the jet propagating through it. The wind outflow scenario may have a different density profile, but the essence of jet dynamics and the nature of an optically thick gas remain unchanged [26]. Since at a distance much larger than the tidal disruption radius the rotation is dynamically unimportant, the strong radiation pressure disperses the marginally bound gas into a quasispherical configuration [23–25]. The density profile in the optically thick envelope can be described by [23,30]

$$\rho_e(r) = \frac{fM_*}{4\pi \ln(R_{\rm out}/R_{\rm in}) r^3} \qquad (1)$$

where M_* is the mass of the disrupted star and $f \simeq 0.5$ is the fraction of the mass in the envelope (which is the mass of the stellar debris that is bound to the massive black hole) and $R_{\rm out}$ and $R_{\rm in}$ are the outer and inner radii of the envelope, respectively. The inner radius is the tidal disruption radius $R_{\rm in} = R_t = R_*(M_{\rm BH}/M_*)^{1/3} \simeq 4\times 10^{13}\ {\rm cm}(M_{\rm BH}/10^7 M_\odot)^{1/3}$, where $M_{\rm BH}$ is the mass of the SMBH and $R_* \simeq R_\odot$ is the initial radius of the disrupted star. $R_{\rm out}$ is the radius where the envelope becomes optically thin, which for electron scattering opacity is given by

$$R_{\rm out} = 1.7\times 10^{15}\ {\rm cm}\left(\frac{fM_*}{0.5M_\odot}\right)^{1/2}. \qquad (2)$$

The propagation of a TDE jet in the extended envelope has been studied with numerical simulations [30]. As the jet advances in the surrounding envelope, the jet drives a bow shock ahead of it. The jet is capped by a termination shock, and a reverse shock propagates back into the jet, where the jet is decelerated and heated. The jet head velocity is obtained by the longitudinal balance between the momentum flux in the shocked jet material and that of the shocked surrounding medium, measured in the frame comoving with the advancing head [31], which gives

$$v_h = \left(\frac{L}{4\pi r^2 c\rho_e}\right)^{1/2} = 10^{10}\ {\rm cm\,s^{-1}} L_{48}^{1/2} r_{15}^{1/2}, \qquad (3)$$

where L is the isotropic luminosity of the jet, $\rho_e \simeq 2\times 10^{-14}\ {\rm g\,cm^{-3}} r_{15}^{-3}$. While the jet is propagating inside the envelope with a subrelativistic velocity, a significant fraction of jet "waste" energy is pumped into the cocoon surrounding the advancing jet [30]. The jet can break out of the envelope if the jet energy supply lasts longer than the breakout time, which is

$$t_{\rm br} = \int \frac{dr}{v_h} = 2\times 10^5\ {\rm s} r_{15}^{1/2} L_{48}^{-1/2}. \qquad (4)$$

Assuming that the mass accretion rate follows the fallback time of stellar material onto the central black hole, matter returns to the region near the pericenter radius at a rate $\dot{M} \propto (t/t_p)^{-5/3}$. The characteristic timescale t_p for initiation of this power-law accretion rate is the orbital period for the most bound matter, which is [32,33]

$$t_p = 1.5\times 10^6\ {\rm s}\left(\frac{M_*}{M_\odot}\right)^{(1-3\xi)/2}\left(\frac{M_{\rm BH}}{10^7 M_\odot}\right)^{1/2} \qquad (5)$$

for a radiative, main-sequence star being disrupted, where $\xi \simeq 0.2$–0.4 is a parameter characterizing the mass-radius relation (i.e., $R = R_\odot(M_*/M_\odot)^{1-\xi}$) [34]. As the jet power may scale with the accretion rate as $L \propto \dot{M}$ in the super-Eddington accretion phase [33], the duration of the jet peak luminosity is t_p, and $L \propto (t/t_p)^{-5/3}$ after that. Comparing this time with the jet breakout time in Eq. (4), we find that powerful jets with $L \geq 10^{46.5} M_{\rm BH,7}\ {\rm erg\,s^{-1}}$ can break out the envelope successfully, while jets with luminosity $L \leq 10^{46.5} M_{\rm BH,7}\ {\rm erg\,s^{-1}}$ would be choked in the envelope. In the latter case, all the jet energy is transferred to the cocoon. If the energy accumulated in the cocoon is larger than the binding energy of the outer part of the envelope, which is about 10^{51} erg for a $10^7 M_\odot$ SMBH, the cocoon may unbind part of the envelope.

At the jet head, reverse shocks heat the jet material and accelerate protons and electrons. Internal shocks may also arise from the internal collisions within the jets resulted from the fluctuations in the jet bulk Lorentz factor Γ [35]. It is thought that the variable x-ray emission of Sw J1644 is produced by internal shocks. As the observed minimum x-ray variability time is $t_v \simeq 100$ s [15], internal shocks may occur at a radius of

$$R \simeq 2\Gamma^2 c t_v = 6\times 10^{14}\Gamma_1^2 t_{v,2}\ {\rm cm}. \qquad (6)$$

TDEs with relativistic jets of $L > 10^{48}\ {\rm erg\,s^{-1}}$ imply accretion rates $> 10^3$ higher than the Eddington accretion rate for $10^7 M_\odot$ black holes. These jets can break free from the optically thick envelopes, and become optically thin after they cleared open channels. There may be less powerful relativistic jets with $L < 10^{48}$ erg s^{-1}, as long as the accretion is super-Eddington. As the bulk Lorentz factor may also be lower for a less powerful TDE jet, the dissipation of the jet energy may occur at radius smaller than 10^{15} cm for internal shocks, well within the optically thick envelope. When $L < 10^{46}$ erg s^{-1}, the jet will be choked and all the dissipation processes can only occur inside the optically thick envelope.

III. NEUTRINO PRODUCTION

We assume that the composition of the jet is mainly protons and electrons. Although, the composition of the nascent jet produced from the central black hole is unknown and could be magnetically dominated. However, as the jet burrows through the surrounding gas, protons from the surroundings could be entrained into the jet. According to numerical simulations of jet propagation [36], Kelvin-Helmholtz instabilities and/or oblique shocks that develop lead to the mixing of surrounding material into the jet while the jet is advancing with a subrelativistic velocity.

Internal shocks and reverse shocks that propagate into the low-density jets are collisionless, although they locate inside the optically thick envelope. CR acceleration is expected as the shocks are not affected by the radiation. This is because the mean-free path of thermal photons propagating into the upstream flow $l_{\rm dec} = (n_j\sigma_{\rm T})^{-1} = 10^{17}$ cm$L_{48}^{-1} r_{15}^2 \Gamma_1^2$ is much larger than the comoving size of the upstream flow $l_u = r/\Gamma = 10^{14}$ cm$r_{15}\Gamma_1^{-1}$ [6], where n_j is the upstream proton density. It has been shown that shocks in TDE jets can accelerate cosmic rays to ultrahigh energies [20–22].

We first consider the neutrinos produced by high-luminosity jets, which can successfully break free from the envelope. The jet clears the material in the channel during the breakout and the radiation from the jet can escape after the jet breaks out. Luminous nonthermal x-ray emission has been seen in three such TDE jets. The x-ray emission should be produced by relativistic electrons accelerated in the jets. The CR protons may interact with these nonthermal x-ray photons and produce neutrinos. The optically thick envelope is likely to be unbounded by the large deposited energy while the jet is propagating, so we do not consider the thermal photons for $p\gamma$ interaction in this case. The effective $p\gamma$ efficiency, defined as the ratio between the dynamic time and the $p\gamma$ cooling time ($f_{p\gamma} \equiv t_{\rm dyn}/t_{p\gamma}$), is

$$f_{p\gamma}(\varepsilon_p) = \sigma_{p\gamma} n'_X (r/\Gamma) K_{p\gamma} \simeq 2 L_{\rm X,48} \Gamma_1^{-2} r_{15}^{-1} \epsilon_{\rm X,KeV}^{-1} \tag{7}$$

where $\sigma_{p\gamma} \simeq 5 \times 10^{-28}$ cm^2 is the peak cross section at the Δ resonance, n'_X is the number density of x-ray photons in the comoving frame of the shock, $\varepsilon_p = 0.15$ GeV$^2\Gamma^2/\epsilon_X = 1.5 \times 10^{16} \Gamma_1^2 \epsilon_{\rm X,KeV}^{-1}$ eV is the proton energy that interacts with x-ray photons, and $\varepsilon_\nu \simeq 7.5 \times 10^{14} \Gamma_1^2 \epsilon_{\rm X,KeV}^{-1}$ eV is the corresponding neutrino energy. Such a high efficiency for $p\gamma$ interactions can be, in fact, inferred from the gamma-ray opacity in three detected TDE jets. Analyses of the Fermi/LAT data of all three jetted TDEs find that they are not detected by Fermi/LAT, with a flux limit in LAT energy being less than 1% of the flux in x rays [27]. The nondetection of high-energy gamma rays is most likely due to the fact that the emitting region is not transparent to these gamma rays, i.e., $\tau_{\gamma\gamma}(\varepsilon_\gamma \geq 100\ {\rm MeV}) > 1$. It is useful to express $f_{p\gamma}$ as a function of the pair production optical depth $\tau_{\gamma\gamma}$. The optical depth for pair production of a photon of energy $\varepsilon_h = 100$ MeV is $\tau_{\gamma\gamma}(\epsilon_h) = \sigma_{\gamma\gamma} n'(\epsilon_t)(R/\Gamma)$, where $n'(\epsilon_t)$ is the number density of target photons, which have an energy of $\epsilon_t = (\Gamma m_e c^2)^2/\epsilon_h = 250$ KeV$(\Gamma/10)^2$. For a power-law spectrum $\beta = 2$ for target photons, we have $f_{p\gamma}(\varepsilon_\nu = 750\ {\rm TeV}) \simeq 0.5\tau_{\gamma\gamma}(100\ {\rm MeV})$. So we reach the conclusion that the pion production efficiency is high for the high-luminosity jets.

Now we consider the neutrino emission produced by low-luminosity, choked jets. The low-density, optically thin jet forms a cavity inside the envelope, while the jets are propagating. The envelope contains dense thermal photons [23], and these thermal photons may diffuse out of the optically thick envelope and enter into the cavity. The energy density in the cavity is hard to estimate and needs a detailed simulation on the jet propagation in the envelope, which is beyond the scope of the present work. We expect that the photon density is significantly suppressed compared to the photon energy density in the envelope. We use f_{ph} to denote the suppression factor in the following estimates. According to [23], the effective temperature at the photosphere $R_{\rm out}$ is $T_p = 2 \times 10^4$ K$(M_{\rm BH}/10^7 M_\odot)^{1/4}$ and the interior temperature scales as $T \propto \rho^{1/3} \propto r^{-1}$, so $T = 4 \times 10^5$ K$(r/10^{14}\ {\rm cm})^{-1}$ at a typical internal shock radius of 10^{14} cm (for $\Gamma \sim 3$ of choked jets). The corresponding photon number density is $n_\gamma = 10^{18} f_{ph}$ cm$^{-3}(r/10^{14}\ {\rm cm})^{-3}$. Then $p\gamma$ interaction with these thermal photons would dominate. The effective pion production efficiency for $p\gamma$ collisions is

$$f_{p\gamma}(\varepsilon_p) = \sigma_{p\gamma} n_\gamma r K_{p\gamma} = 10^4 f_{ph} (r/10^{14}\ {\rm cm})^{-2}. \tag{8}$$

As long as $f_{ph} \geq 10^{-4}$, we expect a significant fraction of the CR proton energy is converted to secondary pions. The CR protons interacting with these soft photons have a typical energy of $\varepsilon_p = 0.15\,{\rm GeV}^2/(3kT) = 1.3 \times 10^{15}$ eV. The corresponding neutrino energy is $\varepsilon_\nu = 0.05\varepsilon_p = 70$ TeV.

For these choked TDE jets, as the neutrino production site is within the optically thick region, the associated high-energy gamma rays cannot escape. Instead, high-energy gamma rays are absorbed by low-energy electrons and photons in the envelope, depositing their energy finally into the envelope. Therefore, these choked TDE jets are also hidden sources of CRs.

IV. CR AND NEUTRINO FLUX

We now estimate the CR and neutrino flux produced by TDE jets. The three TDEs with relativistic jets detected by Swift imply a local rate of $\rho_0 \sim 0.03\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for jet luminosity $L_x \geq 10^{48}\ \mathrm{erg\,s^{-1}}$ [22,37]. The isotropic radiation energies in x rays in all three jetted TDEs are about 3×10^{53} erg [15,18]. Assuming that the total bolometric radiation energy is 3 times larger, the energy injection rate in radiation is about $3\times 10^{43}\ \mathrm{erg\,Mpc^{-3}\ yr^{-1}}$. If the electrons occupy a fraction of $\epsilon_e = 0.1$ of the proton energy, then the energy injection rate in protons is about $\dot{W}_{p,z=0} = 3\times 10^{44}\ \mathrm{erg\,Mpc^{-3}\,yr^{-1}}$. From the kinetic energy of the jet obtained with the radio modeling and assuming a beam factor of $f_b = 10^{-3}$ for relativistic jets, Farrar and Piran [22] obtained a similar energy injection rate, $2\times 10^{44}(f_b/10^{-3})^{-1}\ \mathrm{erg\,Mpc^{-3}\,yr^{-1}}$. This rate is roughly what is needed by the flux of ultrahigh energy cosmic rays, and Farrar and Piran [22] suggested that tidal disruption jets may be the source of ultrahigh energy cosmic rays.

The above estimate does not include the contribution by less powerful ($L < 10^{48}\ \mathrm{erg\,s^{-1}}$) or even choked ($L < 10^{46.5}\ \mathrm{erg\,s^{-1}}$) jets that may be present in normal TDEs. If the jetted TDEs detected by Swift follow the extrapolation of normal TDE luminosity function to high luminosities [37], we would expect that there are more TDEs harboring jets with luminosity of $\sim 10^{46}$–$10^{47}\ \mathrm{erg\,s^{-1}}$. Since the peak accretion rate in TDEs is generally super-Eddington, jet formation is naturally expected in all TDEs. We assume that the majority of normal TDEs have low-luminosity jets with $L \sim 10^{46}\ \mathrm{erg\,s^{-1}}$, so that they are choked and do not have bright radio afterglow emission, consistent with radio observations of normal TDEs [38]. Assuming a peak accretion time given by Eq. (5), the total energy in the choked jet would be $W_p \simeq 10^{51} f_{b,-1}$ erg, where $f_b \simeq 0.1$ is the beam correction fraction. The event rate of normal TDEs is as high as $\rho_0 \sim 10^3\ \mathrm{Gpc^{-3}\,yr^{-1}}$ [39], so the energy injection rate by choked jet could be as large as $10^{45}\ \mathrm{erg\,Mpc^{-3}\ yr^{-1}}$.

To account for the IceCube neutrino flux, the required local energy injection rate is

$$\dot{W}_{p,z=0} = \alpha\left(\frac{c\xi_z}{4\pi H_0}\right)^{-1}\varepsilon_p\Phi_p = 10^{45}\ \mathrm{erg\,Mpc^{-3}\,yr^{-1}}\left(\frac{\alpha}{10}\right) f_\pi^{-1}\left(\frac{\xi_z}{3}\right)^{-1} \times\left(\frac{\varepsilon_\nu\Phi_\nu}{10^{-7}\ \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}}\right) \tag{9}$$

where $\varepsilon_p\Phi_p$ is the proton flux, α is a factor coming from normalization of the proton spectrum [e.g., for a power-law index $s = 2$ of the cosmic ray spectrum, $\alpha = \ln(\varepsilon_{p,\max}/\varepsilon_{p,\min})$], ξ_z is a factor accounting for the contribution from high-redshift sources, and $\varepsilon_\nu\Phi_\nu$ is the all-flavor neutrino flux. Here $f_\pi \equiv 1 - \exp(-f_{p\gamma,pp})$ is the fraction of proton energy lost to pions through $p\gamma$ or pp collision. Since $f_\pi \simeq 1$ for our case, the energy injection rate by TDEs can account for the neutrino flux observed by IceCube at PeV energies and may even account for the higher flux at $\sim$30 TeV if less powerful, choked jets from normal TDEs are included.

V. DISCUSSIONS

Detection of neutrinos from one single TDE jet with a KM^3-scale neutrino detector requires that the source must be extremely bright with a total electromagnetic fluence $\geq 10^{-3}\ \mathrm{erg\,cm^{-2}}$. Among the three TDEs with relativistic jets, only Sw J1644 + 57 has such a large fluence. Thus, the stacking search of a dozen of jetted TDEs is needed to fulfill a promising detection. For choked jets that have an isotropic equivalent energy of 10^{52} erg, detection of one neutrino requires that the TDE should be at a distance within 200 Mpc and that the jet points to the observer. Considering the beam fraction $f_b = 0.1$ of the jet and a TDE rate of $10^3\ \mathrm{Gpc^{-3}\,yr^{-1}}$, the number of such TDEs in the observable volume is only $N = 3f_{b,0.1}$ per year. Thus, the stacking search for neutrinos is also needed for nearby normal TDEs with choked jets.

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