SEARCH FOR HIGH-ENERGY GAMMA-RAY EMISSION FROM TIDAL DISRUPTION EVENTS WITH THE FERMI LARGE AREA TELESCOPE

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ABSTRACT

Massive black holes at galaxy center may tear apart a star when the star passes occasionally within the disruption radius, which is the so-called tidal disruption event (TDE). Most TDEs radiate with thermal emission resulting from the acceleration disk, but three TDEs have been detected in bright nonthermal X-ray emission, which is interpreted as arising from the relativistic jets. A search for high-energy gamma-ray emission from one relativistic TDE (Swift J164449.3+573451) with the Fermi Large Area Telescope (LAT) has yielded nondetection. In this paper, we report the search for high-energy emission from the other two relativistic TDEs (Swift J2058.4+0516 and Swift J1112.2-8238) during the flare period. No significant GeV emission is found, with an upper limit flux in the LAT energy range being less than 1% of that in X-rays. Compared with gamma-ray bursts and blazars, these TDEs have the lowest flux ratio between GeV emission and X-ray emission. The nondetection of high-energy emission from relativistic TDEs could be due to the fact that the high-energy emission is absorbed by soft photons in the source. Based on this hypothesis, upper limits on the bulk Lorentz factors, $\Gamma \lesssim 30$, are then obtained for the jets in these TDEs. We also search for high-energy gamma-ray emission from the nearest TDE discovered to date, ASASSN-14li. No significant GeV emission is found, and an upper limit of $L(0.1–10\text{ GeV}) \lesssim 4.4 \times 10^{42}\text{ erg s}^{-1}$ (at 95% confidence level) is obtained for the first 10$^7$ s after the disruption.

Key words: galaxies: nuclei – gamma rays: galaxies – radiation mechanisms: non-thermal

1. INTRODUCTION

A tidal disruption event (TDE) is an astronomical phenomenon that occurs when a star gets too close to a supermassive black hole in the galaxy center and is disrupted by the tidal force of the black hole. Part of stellar material is bound and accreted by the central black hole, resulting in bright optical, UV, and soft X-ray emission (Rees 1988; Lodato et al. 2015 and references therein). There are a growing number of candidate TDEs being discovered in soft X-ray, ultraviolet, and optical surveys; see Komossa (2015) for a recent review. Recently, three unusual TDE candidate events have been discovered by Swift, i.e., Swift J164449.3+573451, Swift J2058.4+0516, and Swift J1112.2-8238 (hereafter Sw J1644+57, Sw J2058+05, and Sw J1112-82 for short, respectively), which have very bright nonthermal X-ray and radio emissions (Bloom et al. 2011; Burrows et al. 2011; Krimm et al. 2011a, 2011b; Zauderer et al. 2011; Cenko et al. 2012; Brown et al. 2015). The luminous nonthermal X-ray and radio emissions are thought to be produced by relativistic jets (Bloom et al. 2011; Burrows et al. 2011; Levan et al. 2011; Zauderer et al. 2011; Cao & Wang 2012; Metzger et al. 2012; Wang et al. 2014; Liu et al. 2015). Sw J1644+57 shows a highly variable light curve in X-rays, as observed by the X-ray Telescope on board Swift. At redshift $z = 0.354$, the isotropic luminosity of the X-ray emission is as high as $10^{48}$–$10^{49}$ erg s$^{-1}$. Sw J2058+05 exhibits a luminous, long-lived X-ray outburst with an isotropic peak luminosity of $3 \times 10^{47}$ erg s$^{-1}$ (at redshift $z = 1.1853$). Its total isotropic energy (0.3–10 keV) on a timescale of the first 2 months amounts to $10^{54}$ erg. Sw J1112-82 was initially also discovered by Swift/BAT (Burst Alert Telescope) in 2011 June as an unknown, long-lived (order of days) $\gamma$-ray transient source. It exhibits a similar bright X-ray flare, and its position is consistent with the nucleus of a faint galaxy at $z = 0.89$ (Brown et al. 2015). The peak X/$\gamma$-ray luminosity of Sw J1112-82 exceeds $10^{47}$ erg s$^{-1}$.

The nonthermal X-ray emission is thought to be produced by synchrotron radiation of relativistic electrons. One would naturally expect inverse-Compton scattering emission from the same electrons, which may produce high-energy gamma-ray emission. As the three TDEs with relativistic jets emit a total isotropic energy of about $10^{54}$ erg in X-ray band, comparable to or even larger than that in the gamma-ray burst (GRB) prompt emission and blazar flares, one would expect the high-energy gamma-ray emission detectable by the Fermi Large Area Telescope (LAT). Motivated by this, we search for high-energy gamma-ray emission from these three relativistic TDEs.

ASASSN-14li is a normal optically discovered TDE at a distance of about 90 Mpc (Holoien et al. 2016). Transient radio emission has been detected from this event, and modeling of the radio emission gives a kinetic energy of $10^{48}$ erg in a nonrelativistic or mildly relativistic outflow (Alexander et al. 2015; van Velzen et al. 2015). The relativistic electrons producing radio emission may in principle also produce high-energy gamma-ray emission, although the flux level depends on the energy of these electrons and the strength of the magnetic field. It is also proposed that the unbound debris after the disruption will encounter the interstellar medium or dense molecular clouds around the central massive black hole, producing high-energy $\gamma$-ray afterglow through $pp$ collisions (Cheng et al. 2006, 2007; Chen et al. 2015). Thus, we also search for high-energy gamma-ray emission from the normal TDE ASASSN-14li.

The analysis of the Fermi/LAT data of TDEs is presented in Section 2. We present the result for each TDE in Section 3. Furthermore, we compare the high-energy gamma-ray emission...
of relativistic TDEs with that of GRB prompt emission and blazar flares. Then in Section 4, we derive constraints on the bulk motion Lorentz factor of the source based on the nondetection of the high-energy emission. Finally, we give a short summary. Throughout this paper, we take the standard $\Lambda$CDM cosmology with parameters $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$.

2. DATA

2.1. $\gamma$-Ray Data

The Fermi/LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV, and it operates primarily in an all-sky scanning survey mode (Abdo et al. 2009; Atwood et al. 2009). The LAT data currently being released by the FSSC (Fermi Science Support Center) have been processed using the “Pass 8” (P8R2) event-level analysis, and specifically P8R2 source event class data are selected here. The analysis is based on the LAT science tools version v10r0p5. In order to reduce the contamination from Earth Limb emission, less than 52$^\circ$ of the LAT rocking angle and less than 90$^\circ$ of the local zenith angle are required. Moreover, we exclude the time period when the spacecraft is above the South Atlantic Anomaly. We perform an unbinned maximum likelihood analysis of the selected data with the following method. Front-back converting photons (etatype =3) of energies between 100 MeV and 10 GeV are fitted with a power-law spectrum ($N(E) = N_0(E/E_0)^{-\Gamma}$). All events in a region of interest (ROI) of 10$^5$ have been used, and point sources and extending sources within an extra 5$^\circ$ in the LAT 4 yr Point Source Catalog (3FGL) (Acero et al. 2015) are added to the model file. The galactic diffuse and isotropic emission are modeled with gll_iem_v06.fits and iso_P8R2_SOURCE_V6_v06.txt, respectively. When it leaves too many free parameters to gain a good spectral fit for a faint source at a short time interval, we fix the spectral form and free the normalization (“prefactor”) of faint or distant background sources.

For the purpose of comparison, we also analyze the Fermi/LAT data of two typical blazars, i.e., Mrk 421 and 3C 279, during some flare episodes (Hayashida et al. 2012; Bartoli et al. 2015). Analysis threads are similar to the above method. For GRBs, we select the first Fermi/LAT GRB Catalog (Ackermann et al. 2013) as our sample for comparison with TDEs. The processing procedure for the LAT data of GRBs follows our previous work (Tang et al. 2015).

2.2. X-Ray Data

Thanks to Swift/BAT (Gehrels et al. 2004; Barthelmy et al. 2005), for bright X-ray sources such as the three relativistic TDEs mentioned above, we can get the daily average count rate in the survey mode (data quality flag = 0) (Krimm et al. 2013). Because Sw J1644+57 was mistaken for a GRB, it was observed by BAT burst mode and had a good follow-up observation; Burrows et al. 2011.) Considering the limited BAT energy band (15–50 keV), the corresponding flux will be displayed in the spectral energy distribution (SED) plot as one data point.

3. RESULTS

3.1. Sw J1644+57

The likelihood analysis of Sw J1644+57 centered at the position (R.A., decl.) = (251$^\circ$205, 57$^\circ$5810) results in a low TS value (<10), i.e., no significant high-energy emission is found from the BAT trigger time to 100 days after the trigger ($T_0 + 10^7$ s). Its 95% confidence upper limit fluxes are presented in Table 1 for different time intervals.$^6$ We fix the spectral photon index at $\Gamma = -2.0$. Taking different spectral index $\Gamma$ will result in a slight but insignificant difference. We examine the archival database day by day for 3 days before $T_0$ and find nondetection either. Our results are consistent with the results in Burrows et al. (2011), in spite of some slight difference due to new data (PASS 8), different photon index $\Gamma$, and background model. The SED in 0.3–150 keV during the bright period is extracted from Burrows et al. (2011) and plotted in Figure 2. The upper limit fluence in 0.1–10 GeV is $F(0.1–10 \text{ GeV})  \leq 6.30 \times 10^{-6} \text{ erg cm}^{-2}$ during the first 3 days, when the source is in the brightest phase in BAT.

Integrating the BAT emission over the significant emission period, we get a total 15–50 keV fluence of (1.58 $\pm$ 0.1) $\times 10^{-4}$ erg cm$^{-2}$, as shown in Table 2. In order to compare with GRBs, whose fluences are given in the Fermi Gamma-ray Burst Monitor (GBM) band (10–1000 keV), we adopt a power-law spectrum with an index of $-2.15$ ($N(E) = N_0(E/E_0)^{-2.15}$) to extrapolate the 15–50 keV fluence to the 10–1000 keV range, resulting in a 10–1000 keV fluence of about $5.06 \times 10^{-4}$ erg cm$^{-2}$. One can see that the X/$\gamma$-ray fluence is about two orders of magnitude larger than that in 0.1–10 GeV gamma rays.

3.2. Sw J2058+05

The standard gtlklike analysis of the Fermi/LAT data of Sw J2058+05 centered at the position (R.A., decl.) = (314$^\circ$5830, 5$^\circ$2260) gives a nondetection. The upper limit fluxes from the BAT trigger time to 100 days after trigger ($T_0 + 10^7$ s), divided into three time intervals, are given in Table 1 and also shown in Figure 1. Using the BAT and LAT observational data, the SED on 2011 May 23, which is the brightest epoch in BAT, is shown in Figure 2. Sw J2058+05 has a 17-day activity in the BAT observation, with a total fluence of $\approx 1.64 \times 10^{-3}$ erg cm$^{-2}$ when extrapolated to the energy range of 10–1000 keV (see Section 3.1). The corresponding LAT upper limit fluence is $F(0.1–10 \text{ GeV}) \leq 1.67 \times 10^{-5}$ erg cm$^{-2}$ in the same time interval.

3.3. Sw J1112-82

The likelihood analysis of the Fermi/LAT data of Sw J1112-82 centered at the position (R.A., decl.) = (167$^\circ$949, −82$^\circ$6460) also yields a nondetection. The upper limit fluxes from the BAT trigger to 100 days after trigger ($T_0 + 10^7$ s) are given in Table 1 and also shown in Figure 1. We show the BAT and LAT data on 2011 June 16 (the brightest epoch in BAT) in the

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$^6$ LAT upper limit flux is at 95% confidence level if not explicitly specified.

$^7$ As there is no spectral information of TDEs in the range of 10–1000 keV, we check the difference when assuming different photon indices. Taking a photon index of $-1.80, -2.00, -2.15$, and $-2.30$ gives an extrapolation factor of 5.12, 3.82, 3.21, and 2.79, respectively. As the spectrum softens toward the higher energy, as seen in Figure 2 for Sw J1644+57, we adopt $-2.15$ for the estimation.

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http://fermi.gsfc.nasa.gov/ssc/data/

http://swift.gsfc.nasa.gov/results/transients/
The nearest TDE discovered to date, ASASSN-14li, is centered at (R.A., decl.) = (192°063, 17°7739) (Jose et al. 2014). We analyze the Fermi/LAT data during the period from 2014 November 22 to 2015 November 22 and find no evidence of high-energy gamma-ray emission, with a low TS value (<10). The upper limit fluxes are presented in Table 1 and also shown in Figure 1. A search for high-energy gamma-ray emission from the same source in the archival data also yields only an upper limit. At a distance of 90 Mpc, the upper limit luminosity in 0.1–10 GeV is \( L(0.1–10 \text{GeV}) \leq 4.40 \times 10^{42} \text{erg s}^{-1} \) during the period from 2014 November 22 to 2015 March 17. This limit luminosity is lower than the soft X-ray (0.1–3 keV) luminosity, which is about \( 10^{43} \text{erg s}^{-1} \) (Holoien et al. 2016). However, it is higher than the predicted gamma-ray luminosity, \( 10^{39}–10^{40} \text{erg s}^{-1} \), by Cheng et al. (2007), so closer TDEs detected in the future are needed to test the prediction.

### Table 1

| Name       | \( \Gamma \) | Time (s) | Flux (10^{-11}) | Time (s) | Flux (10^{-12}) | Time (s) | Flux (10^{-12}) |
|------------|--------------|----------|----------------|----------|----------------|----------|----------------|
| Sw J1644+57 | 2.0          | 0–10^5   | 2.41           | 10^7–10^8 | 7.63           | 10^6–10^7 | 1.18           |
| Sw J2058+05 | 2.0          | 0–10^5   | 9.74           | 10^7–10^6 | 7.01           | 10^6–10^7 | 7.55           |
| Sw J1112-82 | 2.0          | 0–10^5   | 5.51           | 10^7–10^6 | 25.7           | 10^6–10^7 | 5.75           |
| ASASSN-14li | 2.0          | 0–10^5   | 3.52           | 10^7–10^6 | 19.4           | 10^6–10^7 | 3.96           |

**Note.** Flux is in units of \( \text{erg cm}^{-2} \text{s}^{-1} \) (0.1–10 GeV).

### Table 2

| Name       | MJD (days) | \( \Gamma \) | Flux (0.1–10 GeV) | Flux (15–50 keV) | Flux (10–1000 keV) |
|------------|------------|--------------|-------------------|-----------------|-------------------|
| Sw J1644+57 | 55,648–55,650 | 2.0           | <6.3              | 157.7 ± 10.0     | 506               |
| Sw J2058+05 | 55,698–55,714 | 2.0           | <16.7             | 511.6 ± 118.3    | 1642              |
| Sw J1112-82 | 55,728–55,731 | 2.0           | <9.0              | 299.2 ± 65.7     | 961               |
| Mrk 421     | 55,144–55,149 | 1.57 ± 0.21   | 95.5 ± 19.9       | 638.6 ± 59.3     | 2050              |
|             | 55,242–55,245 | 1.46 ± 0.13   | 135.3 ± 24.3      | 341.0 ± 14.7     | 1095              |
|             | 55,246–55,272 | 1.81 ± 0.08   | 397.0 ± 36.1      | 1761.8 ± 48.9    | 5655              |
|             | 55,475–55,503 | 1.79 ± 0.06   | 561.6 ± 41.9      | 914.1 ± 68.2     | 2934              |
|             | 55,811–55,818 | 1.75 ± 0.11   | 188.2 ± 27.0      | 498.0 ± 47.0     | 1599              |
| 3C 279      | 54,920–54,980 | 2.37 ± 0.03   | 631.1 ± 6.94      | 236.4 ± 116.5    | 759               |
|             | 55,030–55,050 | 2.30 ± 0.01   | 886.7 ± 9.66      | 84.9 ± 68.0      | 273               |

**Note.** The units of flux are \( 10^{-8} \text{ photons cm}^{-2} \text{s}^{-1} \), and the units of the fluence are \( 10^{-6} \text{ erg cm}^{-2} \).

Figure 1. Fermi/LAT (0.1–10 GeV) light curves of four TDEs. The upper limits are at the 95% confidence level.

Figure 2. SED of three relativistic TDEs. The legend “Sw J1644+57 0329” means the spectrum on 2011 March 29. Data marked with blue stars are taken from Burrows et al. (2011).
The nonthermal X-ray emission in three relativistic TDEs may be produced by relativistic electrons via synchrotron radiation (Burrows et al. 2011; Wang & Cheng 2012). The size of the source is estimated to be $L' \sim \Gamma_\ell \theta = 3 \times 10^{13} \text{cm} \Gamma_\ell t_\ell$, where $\Gamma$ is the bulk Lorentz factor of the source, $t_\ell$ is the variability timescale of the source, and $\theta$ is the denotation $Q = 10^{5}Q_{5}$ in the paper. The observed minimum variability time of the X-ray emission in Sw J1644+17 is about $t_\ell = 100s$ (Bloom et al. 2011; Burrows et al. 2011). Assuming that the magnetic field energy density is in equipartition with the radiation energy density, the magnetic field in the comoving frame of the source is estimated to be $B' = (8\pi \epsilon_{BB} L_{X}/4\pi l/2^{\gamma_{B}c}/c)^{1/2} = 3 \times 10^{13} G_{G} \epsilon_{B}^{1/2} L_{X,48}^{1/2} \Gamma_{G}^{-1} \Gamma_{G}^{-1}$, where $\epsilon_{B}$ is the equipartition factor. For such a magnetic field, the X-ray photons with frequency $\nu_{X} = 2 \times 10^{17} \text{Hz}$ are produced by relativistic electrons with Lorentz factors of $\gamma_{e} = (2\pi \epsilon_{eB,\nu_{X}^{0}})^{1/2} \approx 1.5 \times 10^{11/2} \epsilon_{B}^{1/4} L_{X,48}^{1/2} \nu_{X,14}^{-1/2}$. For these electrons, we expect an inverse-Compton (IC) component peaking at $h\nu_{IC} \approx 2\gamma_{e}^{5} \gamma_{e} \approx 5 \text{ GeV}$ when other parameters are taken with typical values. The IC flux should be comparable to or larger than that of the synchrotron component if $\epsilon_{B} \lesssim 1$; thus, we would expect a GeV component with a luminosity of $L_{\text{GeV}} \gtrsim L_{X} \sim 10^{48} \text{ erg s}^{-1}$. The nondetection of such a high-energy component can be attributed to a high absorption opacity due to low-energy photons in the source, i.e., the $\gamma$-ray absorption optical depth should be $\tau_{\gamma} (5 \text{ GeV}) \gtrsim 1$. The optical depth for $\gamma$-ray absorption is given by $\tau_{\gamma} = \sigma_{n'} n' \ell'$, where $\sigma_{\gamma} = \sigma_{\gamma}(1/16)\sigma_{T}$ is the cross section for $\gamma$-ray absorption ($\sigma_{T}$ is the Thompson cross section) and $n'$ is the comoving-frame number density of the target photons that interact with high-energy photons. For high-energy photons with energy $E_{\gamma} = 5 \text{ GeV}$, the energy of the target photons is $\epsilon_{\gamma} \gtrsim 2(\Gamma_{m}c^{2})^{2}/E_{\gamma} = 10 \text{ keV} \Gamma_{G}^{-1} (E_{\gamma}/5 \text{ GeV})^{-1}$. For a power-law spectrum with a photon index of $\beta = 2$ (Burrows et al. 2011), the number density of target photons is $n' \approx L_{X}/(4\pi l^{2} c^{3})$, where $\epsilon_{\gamma}/\gamma_{e}^{5}$. One can derive an upper limit on the bulk Lorentz factor from the condition $\tau_{\gamma} \gtrsim 1$, i.e.,

$$
\Gamma \lesssim \left( \frac{\sigma_{\gamma} L_{X}}{4\pi \epsilon_{e}^{2} \epsilon_{\gamma} \ell} \right)^{1/4} = 30 L_{X,48}^{1/4} \epsilon_{e}^{-1/4} \left( \frac{\epsilon_{\gamma}}{10 \text{ keV}} \right)^{-1/4}.
$$

This shows that the bulk Lorentz factors in TDEs are much lower than those of GRBs (Lithwick & Sari 2001; Tang et al. 2015) and may even be lower than those of some blazars (Savolainen et al. 2010; Wu et al. 2016). There are other possibilities leading to nondetection of high-energy emission from these relativistic TDEs, such as a cutoff in the spectrum of accelerated electrons or a cooling break in the SED. More multiwavelength observations during flaring states will be helpful to diagnose these different assumptions.

5. CONCLUSIONS

We searched for the high-energy gamma-ray emission from TDEs with the Fermi/LAT survey data, including three TDEs confirmed with relativistic jets (Sw J1644+57, Sw J2058+05, Sw J1112-82) and a nearby normal TDE ASASSN-14li. No significant emission is found from these TDEs during the

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The SED is different for different blazars and different flare states of a source; thus, a simple extrapolation factor ($N(E) = N_{0}(E/E_{0})^{-1.5}$) may not be appropriate, but anyway, a few times change of X/$\gamma$-ray (10–1000 keV) fluence will not make the fluence ratio below 1% in Figure 3.

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Figure 3. Fluence measured by Fermi/LAT vs. the fluence measured by Swift/BAT or Fermi/GBM during the X/$\gamma$-ray flare periods for relativistic sources: TDEs, GRBs, and blazars. SGRB and LGRB mean short GRB and long GRB, respectively. The three dashed lines from left to right denote the 100%, 10%, and 1% fluence ratio between 0.1–10 GeV and 10–1000 keV.

3.5. Comparison with GRBs and Blazars

Since relativistic TDEs have relativistic jets similar to GRBs and blazars, we compare the GeV emission in TDEs with the other two relativistic sources. For GRBs, we make the combined GBM-LAT spectral analysis during the prompt emission period, and the data of the GeV fluence and X/$\gamma$-ray fluence are presented in Figure 3, which are consistent with the results in the Fermi/LAT First Gamma-Ray Burst Catalog (see their Figure 17; Ackermann et al. 2013). For blazars, we choose Mrk 421 and 3C 279 as representatives of BL Lac objects and flat-spectrum radio quasars, respectively. We select the time intervals of X-ray emission flares to analyze the Fermi/LAT data (Hayashida et al. 2012; Bartoli et al. 2015). The modeling of the 0.1–10 GeV spectrum of Mrk 421 with a simple power-law function gives a photon index of $\Gamma > -2$, whereas it gives a soft photon index with $\Gamma < -2$ for 3C 279, which are consistent with the statistic characteristic of joint BAT-LAT spectral properties of blazars (Sambruna et al. 2009). Long-time 0.1–300 GeV data give a preferred spectral model logarithmic parabola for 3C 279 in 3FGL, so we check our result with this spectral model and find almost no difference in the fluence. The results of their X/$\gamma$-ray and GeV fluences are listed in Table 2.8

In Figure 3, we compare the X/$\gamma$-ray fluence and GeV fluence of the three types of relativistic sources. We find that all GRBs have GeV fluences larger than 1% of the X/$\gamma$-ray fluences. Among them, a significant fraction of GRBs have GeV fluences larger than 10% of the X/$\gamma$-ray fluence. Blazar flares have similar properties, and all of them have GeV fluences larger than a few percent of the X/$\gamma$-ray fluences. In contrast, the GeV fluences of all three relativistic TDEs are smaller than 1% of the X/$\gamma$-ray fluences. This could be due to the fact that the high-energy gamma-ray emission in TDEs is highly absorbed, as we will discuss below.

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8 The SED is different for different blazars and different flare states of a source; thus, a simple extrapolation factor ($N(E) = N_{0}(E/E_{0})^{-1.5}$) may not be appropriate, but anyway, a few times change of X/$\gamma$-ray (10–1000 keV) fluence will not make the fluence ratio below 1% in Figure 3.
period from the Swift/BAT trigger time (or the inferred disruption time) to about 100 days later. Compared with the bright nonthermal X-ray emission, the nondetection of high-energy emission in three relativistic TDEs implies that high-energy emission is seriously suppressed, possibly due to the $\gamma\gamma$ attenuation by soft photons in the source. Then, we derive upper limits on the bulk Lorentz factors by assuming $\tau_{\gamma\gamma} > 1$ for relativistic jets in TDEs. The nondetection of high-energy emission from the normal TDE ASASSN-14li gives an upper limit of $\left(10^{-4} \text{ GeV s}^{-1}\right)$ during the first $10^7$ s after the disruption, which is already lower than the X-ray luminosity (Holoien et al. 2016), but still higher than the predicted gamma-ray luminosity (Cheng et al. 2007).

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