Searching for High-energy, Horizon-scale Emissions from Galactic Black Hole Transients during Quiescence

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Abstract

We search for the gamma-ray counterparts of stellar-mass black holes using the long-term Fermi archive to investigate the electrostatic acceleration of electrons and positrons in the vicinity of the event horizon. We achieve this by applying the pulsar outer-gap model to their magnetospheres. When a black hole transient (BHT) is in a low-hard or quiescent state, the radiatively inefficient accretion flow cannot emit enough MeV photons that are required to sustain the force-free magnetosphere in the polar funnel via two-photon collisions. In this charge-starved gap region, an electric field arises along the magnetic field lines to accelerate electrons and positrons into ultra-relativistic energies. These relativistic leptons emit copious Gamma-rays via the curvature and inverse-Compton (IC) processes. It is found that these gamma-ray emissions exhibit a flaring activity when the plasma accretion rate typically stays between 0.01% and 0.005% of the Eddington value for rapidly rotating, stellar-mass black holes. By analyzing the detection limit determined from archival Fermi/Large Area Telescope data, we find that the 7-year averaged duty cycle of such flaring activities should be less than 5% and 10% for XTE J1118+480 and 1A 0620-00, respectively, and that the detection limit is comparable to the theoretical prediction for V404 Cyg. It is predicted that the gap emission can be discriminated from the jet emission if we investigate the high-energy spectral behavior or observe nearby BHTs during deep quiescence simultaneously in infrared wavelength and very-high energies.

Key words: black hole physics – gamma rays: stars – magnetic fields – methods: analytical – methods: numerical

1. Introduction

In the past several years, there has been increasing interest in the γ-ray emissions from the direct vicinity of accreting black holes (BHs). Although accreting BHs can emit radiation in various wavelengths in general, only a few of them have confirmed counterparts in the high-energy (HE) γ-ray band. For example, Cyg X-3 (i.e., V1521 Cyg or 4U 2030+40) has a confirmed transient γ-ray detection using the AGILE data above 100 MeV (Tavani et al. 2009) and the Fermi/Large Area Telescope (LAT) data between 100 MeV and 100 GeV (Fermi LAT Collaboration et al. 2009). Cyg X-1 (i.e., V1357 Cyg or 4U 1956+350) also has a confirmed γ-ray counterpart detected by Fermi/LAT between the energy range of 60 MeV and 500 GeV (Zanin et al. 2016). On the other hand, several similar cases did not gain a positive detection in the γ-ray band (Bodaghee et al. 2013). The observed γ-rays were concluded to be associated with the radio flares that are consistent with the radio flux level of the relativistic jets and shock formation in the accretion process. Shocks propagating in a jet (i.e., shock-in-jet model; Marscher & Gear 1985; Björnsson & Aslaksen 2000; Türl er 2011) provide a possible explanation of the very-high-energy (VHE)/high-energy (HE) emission for Cyg X-3 (Miller-Jones et al. 2009; Corbel et al. 2012) and for Cyg X-1 (Malyshhev et al. 2013).

Recently, rapidly varying, sub-horizon-scale TeV emissions were discovered from IC 310 (Aleksić et al. 2014) using Major Atmospheric Gamma-ray Imaging Cherenkov telescopes (MAGIC). The observed radio jet power, the expected cloud crossing time, and the proton–proton cooling time cannot support such models as jet-in-a-jet (Giannios et al. 2010) and clouds/jet interactions (Bednarek & Protheroe 1997; Barkov et al. 2010) for the shock-in-jet scenario. A likely mechanism for such event-horizon-scale γ-radiation is the particle acceleration that takes place in the vacuum gap, which arises in the polar funnel of a rotating BH magnetosphere (Beskin et al. 1992; Hirotani & Okamoto 1998; Neronov & Aharonian 2007; Levinson & Rieger 2011; Broderick & Tchekhovskoy 2015; Hirotani & Pu 2016).

In addition to the emission site, there are several key differences between the shock-in-jet models and the BH-gap models. In the former, the spectrum is determined by the energy releases in the shock, and the spectrum evolves as the shock propagates along the jet with different phases (from Compton to synchrotron to adiabatic phases). A positive correlation between accretion rate and shock emission is expected, provided that jet or outflow become more powerful at higher accretion rates (however, observations of black hole X-ray binaries indicate a complicated disk–jet coupling pattern, see, e.g., Fender et al. 2004). In the latter, the BH-gap model, the rotational energy of a rotating BH is electrodynamically extracted via the Blandford–Znajek process (Blandford & Znajek 1977) and dissipated in the form of charged-particle acceleration, which leads to a resultant γ-radiation from the direct vicinity of the BH. Because the magnetic-field-aligned electric field is less efficiently screened by the created pairs when the soft photon field is weak, the γ-ray luminosity of a
BH gap increases with decreasing mass accretion rate, $\dot{M}$ (Hirotani et al. 2016 hereafter H16). What is more, although Cyg X-3 and Cyg X-1 are persistent BHs in high-mass X-ray binaries (HMXBs) with high accretion rates, $M \sim 3.64 \times 10^{-8} M_{\odot}$ yr$^{-1}$ and $M \sim 3.88 \times 10^{-9} M_{\odot}$ yr$^{-1}$ (Tetarenko et al. 2016; hereafter T16), and serve as examples of the shock-in-jet scenario, the BH-gap model provides an alternative explanation of HE emissions at a lower accretion rate. Furthermore, it is demonstrated in H16 that a BH gap can emit photons mostly in the HE (GeV) range via the curvature process for stellar-mass BHs and mostly in the VHE (TeV) range via the inverse-Compton (IC) process for super-massive BHs.

Motivated by the striking differences between the shock-in-jet and gap-emission scenarios, we expect that only BH transients (BHTs) in quiescence are plausible HE (GeV) gap emitters. As the first trial for seeking possible BH-gap emission from stellar-mass black holes, we select and concentrate on nearby BHTs with low accretion rates in low-mass X-ray binaries (LMXBs) and search for their HE emission by analyzing their 7-year archival data of the Fermi/Large Area Telescope (LAT). In Sections 2–4, we describe how we select the sources, estimate their mass accretion rate, $\dot{M}$, and analyze their LAT archival data. In Section 5, we outline the BH-gap model. In Section 6, we derive the observational upper limits on their HE fluxes and constrain their $\dot{M}$. Finally in Section 7, we compare the expected spectral behavior obtained by the BH-gap and the shock-in-jet scenarios and discuss the next targets to be observed in HE and VHE. The distinct spectral features between the two models should help us discriminate the emission models with future HE observation. Nevertheless, we also emphasise that even for a positive result of HE emission for the sources that have low accretion rates satisfying the requirement of BH-gap models, the shock-in-jet model is not ruled out. The emission nature should be further determined by the overall spectral profile in the HE/VHE region and/or its dependence on $\dot{M}$.

2. Source Selection

Using the recent BH-gap model (H16), we can infer which BHTs will exhibit strong HE and VHE fluxes at Earth. Specifically, we can introduce conditions to search for plausible gap emitters as follows.

1. The BH mass is large.
2. The BH spin is large.
3. The dimensionless accretion rate, $\dot{m}$, lies between $10^{-4.25} \lesssim \dot{m} \lesssim 10^{-4}$ near the horizon, where $\dot{m} \equiv \dot{M}/\dot{M}_{\text{Edd}}$, and $\dot{M}_{\text{Edd}} \equiv 2.18 \times 10^{-8} (M/M_{\odot})(\eta/0.1)^{-1} M_{\odot} \text{yr}^{-1}$ denotes the Eddington accretion rate with accretion efficiency $\eta \sim 10^{-2}$.
4. The distance is short.
5. The observer’s viewing angle, $\zeta_{\text{obs}}$, is relatively small with respect to the rotation axis (i.e., the binary system is nearly face-on; see Section 5.1.2 of H16 for details).

Conditions (1)–(3) represent intrinsic properties, while (4) and (5) show positional conditions relative to us. In general, when the accretion rate is very low, the corresponding radiatively inefficient accretion flow (RIAF) cannot supply enough MeV photons via free–free processes to sustain the force-free magnetosphere (e.g., Figure 1 of H16). In this charge-starved magnetosphere, an electric field inevitably arises along the magnetic field line to accelerate electrons and positrons into ultra-relativistic energies. The resultant gap emission becomes particularly strong when condition (3) is met.

It is noteworthy that persistent X-ray sources will not show strong gap emissions, because their $\dot{m}$ is much higher than condition (3). However, if a BHT has a lower mass-transfer rate (e.g., $M \lesssim 10^{-9} M_{\odot} \text{yr}^{-1}$; Tanaka & Shibazaki 1996), we can expect stronger gap emission from such objects. What is more, we can approximately estimate the gap luminosity from the BZ power (Section 2 of H16) without solving the set of Maxwell–Boltzmann equations (Section 4 of H16), if we impose a condition for the polar funnel to be highly charge-starved. Utilizing this approximation, and using the BH masses and distances reported by T16, we select the top four BH X-ray binaries whose BZ fluxes (i.e., BZ power divided by distance squared) are the greatest at Earth. Among the four objects, we exclude the HMXB Cyg X-1, because its persistent X-ray emission indicates $\dot{m} > 10^{-4}$ in the entire period. Coincidentally, the other three targets all have firm detections of jets, and some studies mentioned in Section 7 are interested in the connection between the jet detection and the HE emission. They are: (i) 1A 0620-00 (i.e., 3A 0620-003 or V616 Mon; Kuulkers et al. 1999), (ii) XTE J1118+480 (i.e., KV UMa; Brocksopp et al. 2010), and (iii) V404 Cyg (i.e., GS 2023+338; Gallo et al. 2005). In this paper, we will examine these three objects as potential gap emitters.

3. Detectability of BH-gap Emission

To infer the feasibility of strong gap emissions, we must estimate the $\dot{m}$ for individual sources. However, such an $\dot{m}$ is, in general, difficult to be constrained on a real-time basis unless the Faraday rotation is measured, as in the case of supermassive BHs (Bower et al. 2003; Kuo et al. 2014). Nevertheless, their long-term averaged values can be estimated as described below.

For 1A 0620-00, the BH mass and the distance are inferred to be $M \approx 6.60 M_{\odot}$ and $d \approx 1.06 \text{kpc}$, respectively, and our viewing angle is reported to be $\zeta_{\text{obs}} = 51^\circ \pm 0.9^\circ$ (Cantrell et al. 2010). From the luminosity of the 1975 outbursts and the interval from the previous one in 1917, the mass accretion rate of 1A 0620-00 can be estimated as $\dot{M} = 3 \times 10^{-11} M_{\odot} \text{yr}^{-1}$ (McCintock et al. 1983), which corresponds to the dimensionless accretion rate $\dot{m} = 2.08 \times 10^{-4}$. During quiescence, its accretion rate can be alternatively estimated by observing its bright spot and can reach up to $M = 3.4 \times 10^{-10} M_{\odot} \text{yr}^{-1}$ (Froning et al. 2011), or equivalently $\dot{m} = 2.36 \times 10^{-3}$, which is one-order higher than the previous measurement. If $\dot{m}$ is close to the former value, $2 \times 10^{-4}$, which is slightly higher than condition (3), 1A 0620-00 is expected to spend a certain fraction of time in the narrow $\dot{m}$ range defined by condition (3), and hence to show HE and VHE flares. However, if the actual $\dot{m}$ is close to the latter value, $2 \times 10^{-3}$, we do not expect that this source undergoes flaring activities during a significant fraction of time. Its $\zeta_{\text{obs}}$ indicates that a strong gap emission may be emitted marginally toward us (H16) if the polar funnel exists down to the lower latitudes (e.g., to the colatitudes $80^\circ$) within $6r_p$ (McKinney et al. 2012).

For XTE J1118+480, we have $M \approx 7.30 M_{\odot}$ (T16), $d \approx 1.72 \text{kpc}$ (Gelino et al. 2006), and $68^\circ < \zeta_{\text{obs}} < 79^\circ$ (Khargharia et al. 2013). Its time-averaged mass accretion rate is estimated to be $\dot{M} = 1.55 \times 10^{-11} M_{\odot} \text{yr}^{-1}$ (updated table
for T16\textsuperscript{6}), or $m = 9.92 \times 10^{-5}$. This small $m$ shows that the BH gap of XTE J1118+480 will exhibit HE and VHE flares a significant fraction of the time. However, its large viewing angle indicates that the BH-gap emission probably propagates away from our line of sight.

For V404 Cyg, we have $M \approx 7.15\,M_\odot$ (T16), $d \approx 2.39\,\text{kpc}$ (Miller-Jones et al. 2009), and $\zeta_{\text{obs}} = 67^{+15}_{-12}$ (Khangharia et al. 2010). Its time-averaged accretion rate is between $2.7 \times 10^{-10} - 3.5 \times 10^{-9}\,M_\odot\,\text{yr}^{-1}$ among its evolution track (King 1993), or $\dot{m} = 1.73 \times 10^{-3} - 2.24 \times 10^{-2}$. But if we consider the updated measurement calculated between 1996 January and 2016 September (updated table for T16 (see footnote 6)), the time-averaged accretion rate is only $2.30 \times 10^{-12}\,M_\odot\,\text{yr}^{-1}$, corresponding to a much smaller $\dot{m} = 1.47 \times 10^{-5}$. If the actual accretion rate is close to the former value, it is very unlikely for V404 Cyg to exhibit a BH-gap emission during a large fraction of the time. However, if it is close to the latter value, its BH gap will exhibit strong HE and VHE emission, which may be stationary or non-stationary, with a large duty cycle. However, its relatively large $\zeta_{\text{obs}}$ may prevent us from detecting these $\gamma$-rays, which may propagate away from our line of sight.

Although the $\zeta_{\text{obs}}$’s of these target sources are large, we examine these three sources as the first step, because the actual $\zeta_{\text{obs}}$ might be different from the represented values mentioned above. Additionally, BHTs in quiescence are known to be variable X-ray sources (Kong et al. 2002). For instance, V404 Cyg can vary by a factor of 20 during quiescence (Kong et al. 2002; Hynes et al. 2004). Thus, during a certain fraction of time, there is a possibility that their $\dot{m}$ enters this relatively narrow range to activate the gap. Given that current observational evidence is not precise enough to determine the time interval for a deep quiescent stage,\textsuperscript{7} as the first trial, we analyze the archival LAT data and examine their time-averaged HE fluxes during 2008 August–2015 November.

4. Observations and Data Analysis

LAT is a wide-band $\gamma$-ray detector (in 20 MeV–300 GeV) on board the Fermi observatory, which has provided an all-sky survey every two orbits since 2008 August. Up until the end of 2015, we already had a 7-year accumulation time for a long-term investigation for those stellar-mass BHTs. For all of the targets in our interest summarized in Section 1, we downloaded the Pass 8 (P8R2) archive from the LAT data server\textsuperscript{8} within a circular FOV in $10^\circ$ radius and considered the time distributed among 2008 August–2015 November for further investigations. For V404 Cyg, which experienced two outbursts in 2015, the photons detected during the first outburst (June/July; Jenke et al. 2016) are removed from the analysis and our data do not cover the epoch of the second outburst (Motta et al. 2015), so that we collect only the photons during low accretion rates.

In order to reduce and analyze data, we used the Fermi Science tools v10r0p5 package and constrain photons in the class for the point source or galactic diffuse analysis (i.e., eclass = 128). We also collected all of the events converting both in the front- and back-section of the tracker (i.e., etype = 3), and the corresponding instrument response described for the selected event type has been defined in the “P8R2\_SOURCE\_V6” IRF (Instrument Response Function) used throughout this study. Events with zenith angles larger than $90^\circ$ were also excluded to avoid the contamination from Earth albedo $\gamma$-rays, and only the good data quality was counted in the time selection to exclude those data within time intervals affected by some spacecraft events (i.e., DATA\_QUAL > 0).

We performed the binned likelihood analysis using the “NewMinunit” optimization algorithm by defining a $7^\circ \times 7^\circ$ square region of interest (ROI), together with the long time span and the energy range of 0.07–300 GeV. The choice for the lower boundary of the energy range was constrained by the usage of IRF to generate the exposure map, and we included the energy dispersion correction when the analysis includes photons <100 MeV. The source model determined for likelihood analysis is based on the LAT 4-year point source (3FGL; Acero et al. 2015) catalog, and the spectral parameters of each source in ROI are freed to gain the best fit to the archival observation. The standard templates of Galactic and isotropic background (gli\_iem\_v06.fits & iso\_P8R2\_SOURCE\_V6.txt) are included in our analysis as well. The central positions determined for our targets are summarized in Table 1, and they can be referred to Gallo et al. (2006), Bailyn et al. (1995), and Miller-Jones et al. (2009, 2011). As all of our targets are not known Fermi sources, a simple power law was adopted to characterize their spectra throughout the analysis. The test-statistic (TS) values yielded with the best fit to observations of the different energy ranges are also reported in Table 1.

5. The Black Hole Gap Model

To compare the LAT observational constraints with the theoretical prediction, we apply the method described in Section 4 of H16 to individual BHTs. Namely, we solve the Poisson equation for the non-corotational potential (Equation (19) in H16) near the event horizon. The magnetic-field-aligned electric field, $E_\parallel$, can be computed from the Poisson equation through Equation (23) of H16. Second, we solve the Boltzmann equations of the produced $e^\pm$’s in the gap, assuming that their Lorentz factors saturate at the curvature-limited terminal value at each position. This assumption is valid for stellar-mass BHs, because the curvature process dominates the IC one, and because the acceleration length is shorter than the gap width, particularly during the HE flare. Third, we solved the radiative transfer equation of the emitted photons, assuming they have vanishing angular momenta.

We adopt the analytic solution of Mahadevan (1997) to describe the RIAF soft photon, and solve the gap in the 2D poloidal plane (Section 4.2.5 of H16). Both the outer and inner boundary positions were solved from the free boundary problem. To estimate the greatest gap flux, we adopt $a_\ast = 0.9$ and $\Omega_b = 0.5\omega_\text{H}$, where $a_\ast = a/r_g$ is the dimensionless BH’s spin parameter, and $r_g = GMc^{-2}$ represents the gravitational radius; $\omega_\text{H}$ and $\omega_\text{H}$ denote the angular frequency of rotating magnetic field lines and a rotating BH, respectively. We assume that the magnetic field takes the equipartition value with the plasma accretion,

$$B = B_\text{eq} \approx 4 \times 10^{8}\dot{m}^{1/2}M_1^{-1/2}G,$$

at $r = 2r_g$, where $M_1$ denotes the BH mass in ten solar-mass units.
6. Results

In spite of the long-term accumulation of the Fermi data, we did not detect any counterparts at a significant level for all the three sources we have considered. This result is consistent with sources resolved in the 4-year Fermi catalog (Acero et al. 2015) and the examination for V404 Cyg using 7 year LAT data (Loh et al. 2016). We also tried the energy-resolved investigations as well; however, the corresponding γ-rays emitted from the direction of the source position are still too few to show any clean signature in the binned likelihood analysis. Assuming a simple power-law spectrum, we find that the spectral parameters have very large uncertainties in this case.

On these grounds, we list their 2σ flux upper limits in Table 1, according to the best spectral fit obtained in the analysis. It is also noteworthy that the VHE flux may be detectable below 1 TeV during a HE flare, as indicated by the sensitivity curves of Cherenkov Telescope Array (CTA) in Figures 1–3 (dashed and dotted curves labelled with “CTA 50 hr”). In all of the figures, we put these upper limits on the predicted spectra of their BH-gap emissions.

Figure 1 shows the case of 1A 0620-00. The cyan dashed–dotted, blue dotted, green dashed–dotted–dotted–dotted, black solid, and red dashed lines correspond to the dimensionless accretion rates, $\dot{m} = 1.00 \times 10^{-3}$, $10^{-3.5}$, $10^{-4}$, $10^{-4.25}$, and $10^{-4.425}$, respectively. The latter three lines show that the fluxes fall below 1–3 GeV via curvature process and in 0.03–1 TeV via IC process, when the dimensionless accretion rate is between $5 \times 10^{-5}$ and $10^{-4}$. We then put the flux upper limits (obtained from the 7-year LAT archival data as described above) with the two red down arrows in 0.1–1 GeV and 1–10 GeV. It follows that the flaring HE fluxes, which are represented by the green, black, and red lines, are predicted to be 10–20 times greater than the observational upper limits. Thus, we find that the 7-year averaged duty cycle of such flaring activities was less than 10% from 2008 August to 2015 November for 1A 0620-00, provided that $a_* > 0.9$ and $\zeta_{obs} < 40^0$ (H16), and adopting a conservative flux estimate at $\dot{m} = 10^{-4}$. For instance, if the BH gap flares during 10% of the entire period, its flux is predicted to appear at (or slightly above) the 10% level of its peak, which is comparable with the observational upper limit (red down arrow). However, if its BH is rotating as slowly as $a_* \sim 0.12$ (Bambi 2016), there is no chance for such a slow rotator to emit a detectable flux at Earth from its gap; that is, we will not be able to obtain any constraints on the duty cycle of HE flares, using the BH-gap model.

Note.  
$^a$ The 2σ flux upper limit was derived by the best fit with a single power law to describe the spectrum.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Spectral energy distribution (SED) of the gap emission from 1A 0620-00 with BH mass of $M = 11 M_\odot$, dimensionless spin of $a_*=0.9$, and distance of $d = 1.16$ kpc. The lines correspond to different dimensionless accretion rates, $\dot{m} = 1.00 \times 10^{-3}$ (cyan dashed–dotted), $10^{-3.5}$ (blue dotted), $10^{-4}$ (green dashed–dotted–dotted–dotted), $10^{-4.25}$ (black solid), and $10^{-4.425}$ (red dashed), respectively. A stationary vacuum gap is expected to take place at $0.1 \lesssim \dot{m} < 10^{-4}$. The thin curves on the left denote the input ADAF spectrum, while the thick lines on the right do the output gap spectra. The red down arrow shows the upper limit flux obtained by re-analyzing the Fermi/LAT archival data. The thin dashed and dotted curves (with horizontal bars) denote the CTA detection limits after a 50-hr observation. Magnetic field strength is assumed to be the equipartition value with the plasma accretion.

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Same as Figure 1 but for XTE J1118+480, with $M = 7.48 M_\odot$, $a_*=0.9$, and $d = 1.72$ kpc. The lines for the gap model correspond to the same $\dot{m}$ as Figure 1.

In the same way, we also apply the BH-gap model to the two other targets and generate the predicted spectra (Figures 2 and 3). Comparing with the observational upper limits (red down arrows) obtained by the binned likelihood analysis with...
Figure 3. Same as Figure 1 but for V404 Cyg, with $M = 12 \, M_\odot$, $a_\ast = 0.9$, and $d = 2.39$ kpc. The lines for the gap model correspond to the same $\dot{m}$ as Figure 1.

long-term Fermi archive, we find that the duty cycle of the BH gap is less than 0.05 (i.e., 5\%) for XTE J1118+480, provided that $a_\ast > 0.9$ and $\zeta_{\text{obs}} < 40^\circ$. For V404 Cyg, the predicted HE flux lies at the same level of the observational upper limits. Thus, we cannot constrain the duty cycle of its gap flares.

Lastly, we would like to comment on the dependence between $a_\ast$ and BZ power. The BZ power, and hence the gap luminosity is approximately proportional to $a_\ast^{-2}$. (It is noteworthy that the BH-gap emission and the jet HE emission are independent each other.) Thus, the predicted flux is approximately halved if $a_\ast$ reduces from 0.90 to 0.45, for instance. In the case of a smaller $a_\ast$, the upper limit of the gap flaring duty cycle will be less constrained. On the other hand, if $a_\ast > 0.95$ is observationally confirmed, it is no longer valid to assume a constant radial magnetic field, $B' \propto F_\nu \sqrt{-g}$, on the horizon, where $F_\nu$ denotes the meridional derivative of the magnetic function, and $\sqrt{-g}$ the volume element (Tanabe & Nagataki 2008; Tchekhovskoy et al. 2010). Such an extremely rotating case will be investigated in a separate paper.

7. Discussion

The non-detection of the HE fluxes from any of the three sources may indicate either that their long-term accretion rates are above condition (3) (i.e., $\dot{m} > 10^{-4}$, see Section 2) so the duty cycle of the gap activity is weak, or that our line of sight misses their $\gamma$-ray flares. It is also possible that the BH spin is actually less than what we assumed. For example, even for 1A 0620-00 or XTE J1118+480, it is very unlikely to detect their BH-gap emission with LAT even if its flaring duty cycle is nearly 100\%, if $a_\ast < 0.25$. Nevertheless, in general, there might be a greater possibility for a BH binary to show detectable gap emission if its time-averaged accretion rate is moderately small, and if we view the binary almost face-on. We can expect a small accretion rate for the sources that stay in long quiescence and their recurrence time is long. For instance, if we simply assume a BH mass of 10 $M_\odot$, XTE J1818-245 is estimated to have relatively close accretion rate to condition (3) (T16), although it does not have confirmed $M$, or $\zeta_{\text{obs}}$ yet. Such a source is located within several kpc (e.g., in the near side of our Galaxy), and its BH-gap emission may be detectable during its deep quiescence if we are lucky and view them almost face-on (condition 5). Because the accretion rate is variable, it is desirable to observe the aforementioned BHTs frequently during their quiescence in near-IR and/or VHE, in order not to miss their gap flares. For example, once the near-IR flux decreases enough, we suggest to observe the source with ground-based, Imaging Atmospheric Cherenkov Telescopes (IACTs) to detect their BH-gap emission below a few TeV. In this case, X-ray flux is predicted to be very weak.

On the contrary, if we detect an HE flare contemporaneously with an X-ray flare (i.e., during its high accretion rate phase), this suggests that these photons are emitted from the jet, rather than the BH gap. Thus, contemporaneous observations at X-ray and HE ranges will help us discriminate the emission processes in accreting BH systems. One similar example is the investigation of V404 Cyg during its 2015 X-ray outburst in June using the Swift/BAT, INTEGRAL/ISGRI, and Fermi/LAT data (Loh et al. 2016). Even with the consideration of local time bin (i.e., 6 hr), the detection significance yielded from the unbinned likelihood analysis for the $\gamma$-ray data is still less than 4$\sigma$. Piano et al. (2017) considered the AGILE data in the 50–400 MeV energy band and improved the significance of the source detection to $\sim 4.3\sigma$. Inverse-Compton scattering of photons that aims to explain the transient $\gamma$-rays detected for Cyg X-3 (Acero et al. 2015) can provide a similar scenario to support the simultaneous detection of radio outburst, pair annihilation, and HE $\gamma$-rays for V404 Cyg. However, the strong cut-off observed in the HE emission of $\sim 400$ MeV may provide a constraint to classify such a detection. The question of whether there exists a similar spectral component for the hard X-ray and $\gamma$-ray or not can also serve to unambiguously confirm the emission mechanism of the traditional shock-in-jet approach.

Due to either the non-detection of the HE emission or the correlation between the accretion rate and the HE flux, we cannot specify whether the shock-in-jet or the BH-gap model is responsible for these sources. To gain more insights into the differences between the gap model and the shock-in-jet model, we can compare the spectral features of both models. In the gap of a stellar-mass black hole, essentially all of the electrons have the same Lorentz factor at each position, because their motion is saturated by the curvature radiation drags. On the contrary, in the shock-in-jet scenario, the electron is heated at the shock, resulting in a wider energy distribution than those that are electromagnetically accelerated in the gap. There exists a characteristic slope for the shock-in-jet model of the optically thin flux density, $\nu S_\nu \propto \nu^{-0.5}$, during the so-called “Compton stage” (Marscher & Gear 1985). During this stage, the energy density of the magnetic field is much larger than the energy density of photons when the shock propagates along the jet. With $s \approx 2.1$ (Sironi & Spitkovsky 2011), a characteristic slope of $\nu S_\nu \propto \nu^{-0.05}$ is estimated. The range of such a slope is related to the electron energy distribution, and the normalization is determined by the strength of the shock. It is, therefore, possible to distinguish the responsible emission models according to the high-energy spectral profile. Namely, in the gap model, a bumpy spectrum is expected due to the nearly mono-energetic distribution of electrons. On the other hand, in the shock-in-jet model, a smoother, single power law is expected due to a much wider, power-law energy distribution of electrons. With the current result of non-detection, there is no observational preference for either model.
Moreover, inclusion of lower-energy observations are also useful in discriminating the emission models. It follows from Figures 1–3 that the gap HE and VHE fluxes increase with decreasing $m$. That is, we can predict an anti-correlation between the IR/optical and HE/VHE fluxes (H16). This contrasts the standard shock-in-jet scenario, in which the IR/optical and the HE/VHE fluxes will correlate. If their time-varying multi-wavelength spectra show anti-correlation, it strongly suggests that the photons are emitted from the BH gap. With the observational upper limits of the individual sources and the upper limits predicted by the BH-gap model, we can constrain their mass accretion rate, $M$. This is potentially important for the discussion of their binary evolution through the long-term accretion rate. Therefore, we propose to simultaneously observe nearby LMXBs that have more massive BHs during deep quiescence in near-IR/optical, X-ray, HE, and VHE (with CTA) in the future.

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Facility: Fermi (LAT).

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