Could an X-ray Flare after GRB 170817A Originate from a Post-merger Slim Accretion Disc?

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ABSTRACT

GRB 170817A, detected by Fermi-GBM 1.7 s after the merger of a neutron star (NS) binary, provides the first direct evidence for a link between such a merger and a short-duration gamma-ray burst. The X-ray observations after GRB 170817A indicate a possible X-ray flare with a peak luminosity $L_{\text{peak}} \sim 2 \times 10^{40}$ erg s$^{-1}$ near day 156. Here we show that this X-ray flare may be understood based on a slim disc around a compact object. On the one hand, there exists the maximal accretion rate $\dot{M}_{\text{max}}$ for the slim disc, above which an optically thick outflow is significant and radiation from the disc is obscured. Based on the energy balance analysis, we find that $\dot{M}_{\text{max}}$ is in the range of $\sim 4 \dot{M}_{\text{Edd}}$ and $\sim 21 \dot{M}_{\text{Edd}}$ when the angular velocity of the slim disc is between $(1/5)^{1/2} \Omega_K$ and $\Omega_K$ (where $\dot{M}_{\text{Edd}}$ is the Eddington accretion rate and $\Omega_K$ is the Keplerian angular velocity). With $\dot{M}_{\text{max}}$, the slim disc can provide a luminosity $\sim L_{\text{peak}}$ for a compact object of $2.5 M_\odot$. On the other hand, if the merger of two NSs forms a typical neutrino-dominated accretion disc whose accretion rate $\dot{M}$ follows a power-law decline with an index $-1.8$, then the system must pass through the outflow regime and enter the slim disc in $\sim 11 - 355$ days. These results imply that a post-merger slim accretion disc could account for the observed late-time $L_{\text{peak}}$.

Key words: accretion, accretion discs—gamma-ray burst: general — X-rays: general

1 INTRODUCTION

Gamma-ray bursts (GRBs) are short-duration flashes of gamma-rays occurring at cosmological distances. An extremely low-luminosity GRB 170817A was detected by Gamma-ray Burst Monitor (GBM) on board the Fermi satellite at 12:41:04.446 UTC as a short GRB (Goldstein et al. 2017). This burst is highly noticeable due to its connection to the gravitational wave event GW170817 which was detected by the Laser Interferometer Gravitational-wave Observatory (LIGO) approximately 1.7 s before the GBM triggered (Abbott et al. 2017). A few hours later, GW170817 was further identified to originate from a binary neutron star (NS) merger, thanks to the discovery of an associated kilonova (Arcavi et al. 2017). This is the first direct evidence for a link between NS-NS mergers and short GRBs. In addition, the gamma-ray signal of GRB 170817A and the following emission are unlikely to be those of any other short GRB seen before (Kasliwal et al. 2017; Matsumoto et al. 2019). Compactness arguments reveal that the observed gamma-rays may be produced in a mildly or fully relativistic outflow (Kasliwal et al. 2017). There are also arguments that the gamma-rays may be generated when a cocoon breaks out from the merger ejecta, where the cocoon arises from either an emerging or a choked jet (Gottlieb et al. 2018; Nakar et al. 2018). A plausible explanation for the observed emission is synchrotron radiation from the fast tail of dynamical ejecta during the merger or from electrons accelerated through a forward shock driven by the merger outflow (Hotokezaka et al. 2018; Nakar & Piran 2018).

X-ray flares are erratic temporal features, commonly seen in GRB afterglows, and have been observed both in long and short GRBs (e.g., Romano et al. 2006; Campana et al. 2006; Falcone et al. 2006; Margutti et al. 2011). They usually happen at $10^2$ – $10^3$ s after the prompt emission, a few flares can occur even up to several days after the GRB trigger (e.g., Chincarini et al. 2007, 2010; Falcone et al. 2007). The fluence of an X-ray flare is usually smaller than that of the prompt emission and the temporal behaviour of flares is quite similar to the prompt emission pulses. Thus, X-ray flares may have the same physical origin as the
prompt pulses (Burrows et al. 2005; Falcone et al. 2006, 2007; Zhang et al. 2006; Nousek et al. 2006; Liang et al. 2006; Chincarini et al. 2007, 2010; Wu et al. 2013; Yi et al. 2015), and may provide an important clue to understand the mechanism of GRB phenomenon. The physical origin of X-ray flares remains mysterious, including late-time activity of the central engines (e.g., Falcone et al. 2007; Chincarini et al. 2007, 2010; Bernardini et al. 2011; Mu et al. 2016, 2018), fragmentation of the accretion disc (Perna et al. 2006), intermittent accretion behaviour caused by a time variable magnetic barrier (Proga & Zhang 2006), magnetic reconnection from a post-merger millisecond pulsar (Dai et al. 2006) and magnetic dissipation in a decelerating shell (Giannios 2006).

The X-ray observations have shown that GRB 170817A has an X-ray flare occurring between day 155 and 157 after prompt emission, followed by a rapid decay phase, which suggests that the X-ray emission peaked at day 156 (Piro et al. 2019). The peak time $t_{peak} \approx 156$ d and the peak luminosity $L_{peak} \sim 2 \times 10^{39}$ erg s$^{-1}$ with the distance $D_L = 40$ Mpc, fall within the expected range of values derived by an extrapolation the flux distribution of GRB X-ray flares to later times (Bernardini et al. 2011; Piro et al. 2019). The idea of X-ray emission from late-time accretion around a neutron star merger remnant have been addressed extensively generally (Rosswog 2007; Metzger et al. 2010; Fernández et al. 2015) and in the context of GRB 170817A (Kisaka et al. 2015; Matsumoto et al. 2018). Here we show that the late-time X-ray flare after GRB 170817A may be understood based on a slim disc model.

The slim disc model (Abramowicz et al. 1988) is introduced for super-Eddington accretion flows with the mass accretion rate $\dot{M} > \dot{M}_{edd}$, where $\dot{M}_{edd} = 64\pi GM/cK_{vis}$. Here $M$ is the mass of a black hole (BH), $c$ is the speed of light, and $K_{vis} = 0.4$ cm$^2$ g$^{-1}$ is the electron scattering opacity. The local analysis reveals that there may exist the maximal accretion rate $\dot{M}_{max}(\nu) = \pi \rho \Omega^2 \nu^{1/2} \Delta z$ at a radius of the slim disc (Gu & Lu 2007; Cao & Gu 2015). Global transonic solutions for slim discs with the explicit vertical gravitational force confirm that the possible maximal accretion rate indeed occurs for a slim disc (Jiao et al. 2009). The physical reason for this may be related to the limited cooling by advection and radiation and therefore no thermal equilibrium can be established for $\dot{M} > \dot{M}_{max}$ (Gu 2015). As a consequence, outflows ought to occur in such flows. The previous simulations have also found strong outflows for extremely high accretion rates (e.g., Ohshiga & Mineshige 2011; Sadowski & Narayan 2016).

In this paper, we focus on the timescale and the luminosity of the X-ray X-ray flare after GRB 170817A and show that such properties may be understood based on a slim disc around a post-merger compact object. This paper is organized as follows. The physical model is presented in §2. Results are presented in §3. Conclusions and discussion are given in §4.

## 2 PHYSICAL MODEL

If the merger of double NSs forms a typical neutrino-dominated accretion disc, then the accretion rate $\dot{M}$ may follow a power-law decline with an index of $-5/3$ (Rees 1988). Recently, a power-law fit to the accretion rate in the GRMHD (general-relativistic magnetohydrodynamic) model for $t > 1$ s yields $t^{-1.8}$ (Fernández et al. 2019; Siegel & Metzger 2018), that is,

$$M = M_j(t/t_s)^{-1.8},$$

and thus the timescale towards the slim disc regime $t_{ph}$ can be estimated as

$$t_{ph} = t_s(M_j/M_{ph})^{5/9},$$

where $t_s = 2$ s is the duration of GRB 170817A, and $M_j$ is the accretion rate of the neutrino-dominated accretion disc in the range of $0.001 - 0.1 M_{\odot}/s^{-1}$. Here, the lower limit of $0.001 M_{\odot}/s^{-1}$ is known as the ignition accretion rate (Chen & Beloborodov 2007), and the upper limit of $0.1 M_{\odot}/s^{-1}$ can be estimated by the prompt gamma-ray emission duration 2 s and an upper limit of the disc mass $\sim 0.2 M_{\odot}$. Thus, if the typical accretion rate $M_{ph}$ is given, we can predict the time of reaching the slim disc regime. We derive such a typical rate $M_{ph}$ as follows.

In the energy balance equation for super-Eddington accretion flows, the viscous heating rate equals the cooling rate, where the cooling mechanisms include advection, radiation and outflows, and therefore we have

$$Q_{vis} = Q_{rad} + Q_{adv} + Q_{outflow},$$

where $Q_{vis}$ is the viscous heating rate, $Q_{rad}$ is the radiative cooling rate, $Q_{adv}$ is the advective cooling rate, and $Q_{outflow}$ is the cooling rate by outflows.

For super-Eddington accretion flows with high accretion rates, the advective cooling rate may be limited to be under 30% of the viscous heating rate (Gu 2015). We assume that a necessary condition for the slim disc regime is that the radiative cooling should be significant. Otherwise, the cooling ought to be dominated by outflows, in which case the radiation of the disc is obscured by the dominant optically-thick outflows. Thus, we assume the following condition,

$$Q_{rad} > \frac{1}{2} Q_{vis}.$$

In general, we have a relation between the radiative cooling rate and the vertical energy flux,

$$Q_{rad} = 2F_z,$$

where $F_z$ is the radiative energy flux in $z$-direction. The gravitational force in the vertical direction, $\kappa_{vis}/c \cdot F_z$, has a maximum value (Cao & Gu 2015)

$$\frac{\kappa_{vis}}{c} \cdot F_z \leq \left( \frac{d\Phi}{dz} \right)_{\text{max}},$$

where $\Phi$ is the gravitational potential. The vertical component of gravity of the BH increases from the mid-plane of the disc along $z$, and reaches the maximum at $z/R = \sqrt{2}/2$, where $R$ is the radius (Cao & Gu 2015).

We adopt the Paczyński-Wiita potential (Paczyński & Wiita 1980),

$$\Phi = -\frac{GM}{\sqrt{R^2 + z^2}} - R_k,$$

where $R_k = 2GM/c^2$ is the Schwarzschild radius. The expression for $Q_{vis}^+$ is

$$Q_{vis}^+ = \frac{3}{8\pi} \dot{M} \Omega^2 \left( 1 - \frac{j}{\Omega R^2} \right) \left( \frac{2d\ln \Omega R}{3d \ln R} \right),$$

where $\Omega$ is the angular velocity, $j$ is the specific angular momentum of the disc, and $d\ln \Omega R$ is the change in the angular velocity of the disc along $z$.
where $j$ is an integration constant determined by the zero-torque boundary condition at the last stable orbit, representing the specific angular momentum per unit mass of the material accreted by the BH, $\Omega$ is the angular velocity, and $\Omega_k^2 = GM/(R - R_g)^2$. It is known that the slim disc rotates in a sub-Keplerian manner (Abramowicz et al. 1988). We therefore assume that $\Omega = \Omega_k$ and $0 < \lambda < 1$, where the parameter $\lambda$ can be estimated from previous self-similar solutions.

### 3 RESULTS

Based on Equations (3)-(8), we take $R = 10R_g$ as a typical radius for analysis, $\lambda = (1/5)^{1/2}$ for slim discs (Wang & Zhou 1999), and $j$ is assumed to be $1.8cR_g$. As a consequence, the maximal accretion rate can be derived as $\dot{M}_{\text{max}} = 21M_{\text{Edd}}$, for which Inequality (4) matches the boundary $Q_{\text{rad}}^- = Q_{\text{vis}}^+$. If the slim disc rotates in a Keplerian manner, then the maximal accretion rate is $4M_{\text{Edd}}$. Figure 1 shows the accretion rate $\dot{M}$ as a function of time $t$. The two red horizontal lines represent the maximal accretion rate $21M_{\text{Edd}}$ and $4M_{\text{Edd}}$, and the blue vertical line corresponds to 156 days. For the accretion rates, there are two regions for thermal equilibrium solutions without strong outflows. One region has a relatively high accretion rate, $0.001 - 0.1M_\odot \text{s}^{-1}$ (two black horizontal lines), corresponding to the neutrino-cooled discs for the central engine of GRBs. The other has a relatively low rate, $\dot{M}_{\text{Edd}} \lesssim \dot{M} \lesssim \dot{M}_{\text{max}}$, corresponding to the photon radiation-dominated discs, where X-ray radiation is the dominant mechanism. The two regions are plotted in Figure 1. As shown by Figure 1, between these two regions, outflows ought to be optically thick and dominate, so that the radiation from the disc is obscured. The two green lines show that the accretion rates follow a power-law decline with an index of $-1.8$. The cross points of the $21M_{\text{Edd}}$ and the two green lines are $t \approx 11$ and 145 days. The cross points of the $4M_{\text{Edd}}$ and the two green lines are $t \approx 28$ and 355 days. It is seen from Figure 1 that the cross point of the red lines and the blue line (156 days) is nearly located between the two green lines. Our calculations above do not take into account the spin of the BHs. If the spin of the BHs is considered, the energy release efficiency of accretion discs should be improved, so that the maximum accretion rate will be reduced, which makes the intersection time longer, which means that the time of the accretion disc reaching the slim disc, according to our model, is in agreement with the observations.

Therefore, our scenario for the observed late-time X-ray flare is described as follows. After the prompt gamma-ray emission, the accretion rate varies following a power-law decline with an index of $-1.8$, and thus the accretion flow will first enter an outflow-dominated regime ($21M_{\text{Edd}} - 0.001M_\odot \text{s}^{-1}$ or $4M_{\text{Edd}} - 0.001M_\odot \text{s}^{-1}$). In such a case, the dominant optically thick outflow can prevent the X-ray emission of the accretion flow from being observed. That is why the X-ray luminosity is quite low for the system in the "outflow-dominated" region (Figure 1), even though the accretion rate may be extremely high. On the contrary, when the accretion approaches the maximal rate of a slim disc, the outflow will become weak and the observed X-ray emission from the accretion flow will reach the peak luminosity. Finally, following the decline in the accretion rate, the inflow will become around Eddington and then sub-Eddington. Consequently, the X-ray luminosity will drop to a low level. From the physical point, the observed X-ray flare is related to a power-law decline for the accretion rate and the occurrence of a strong optically thick outflow for an accretion rate beyond the maximal value of a slim disc.
Now we investigate the typical luminosity when the accretion enters the slim disc region. Some previous theoretical works have provided the disc luminosity as a function of accretion rate (e.g., Equation 10.27 of Kato et al. 2008).

\[
\frac{L}{L_{\text{Edd}}} \simeq \left\{ \begin{array}{ll}
1 + \ln\left(\frac{\dot{m}}{\dot{m}_0}\right), & \dot{m} \geq \dot{m}_0, \\
\frac{\dot{m}}{\dot{m}_0}, & \dot{m} < \dot{m}_0,
\end{array} \right.
\]

where \(\dot{m} = \dot{M}/\dot{M}_{\text{Edd}}\) and the difference in efficiency for the supercritical BH accretion model is taken into consideration. Such a relation is shown by the black solid line in Figure 2.

Narayan et al. (2016) showed that the isotropic equivalent luminosity \(L_{\text{iso}}\) of the supercritical BH accretion model is related to the inclination angle \(\theta\). So, for the luminosity of the X-ray flare after GRB 170817A near day 156, we should consider the factor \(1 - \cos \theta\). Since \(\sim 2 \times 10^{38}\text{erg s}^{-1}\) is around the typical luminosity provided by a slim disc around a compact object (e.g., stellar-mass BH or NS). The half-thickness of the slim disc may range from \(H/R \sim 1/\sqrt{3}\) (Wang & Zhou 1999) to \(H/R \sim 1\) (Abramowicz et al. 1995), and then the corresponding luminosity \(L_{\text{disc}}\) ranges from \(\sim 1.2 \times 10^{39}\text{erg s}^{-1}\) to \(\sim 5.8 \times 10^{39}\text{erg s}^{-1}\). The two horizontal lines represent the luminosity \(L_{\text{disc}}\) of the maximal accretion rate from \(4\dot{M}_{\text{Edd}}\) to \(21\dot{M}_{\text{Edd}}\). The shaded part of light blue shows the maximum accretion rate between \(4\dot{M}_{\text{Edd}}\) and \(21\dot{M}_{\text{Edd}}\). The intersection of the two horizontal lines and light blue shadows are represented by the green shadow region. We can see that the black solid line lies in the middle of this green shadow region.

This means that, if the vertical advection process can play a role, then the radiation from the maximal accretion rate can well explain the observed peak luminosity of the X-ray flare. Thus, we suggest that the central engine for the observed late-time X-ray flare may be related to the super-Eddington accretion process.

4 CONCLUSIONS AND DISCUSSION

We have proposed that if the accretion rate follows a power-law decline with a typical index of \(-1.8\), then the observed late-time X-ray flare after GRB 170817A around day 156 can be well explained by a slim disc surrounded by a stellar-mass BH. If the vertical advection process found in simulations can play a role, a slim disc with the maximal accretion rate can provide the observed peak luminosity. We therefore suggest super-Eddington accretion as a central engine of the X-ray flare. The physics of the observed late-time X-ray flare is related to a power-law decline for the accretion rate and the occurrence of a strong optically thick outflow for an accretion rate beyond the maximal value of a slim disc.

On the other hand, if the central object is a neutron star rather than a black hole, the slim disc model may still work except for the most inner regions. Since the neutron star has a hard surface instead of a horizon, the trapped photons in the slim discs cannot be absorbed by the neutron star. A possible scenario is that, for the same super-Eddington accretion rate, outflows in a neutron star system may be even stronger, and they can carry away the trapped photons outwards and a part of the photons can be released far away from the disc. Following this argument, the slim disc around a neutron star may also be responsible for the late-time X-ray flare. The difference may be that the maximal accretion rate in the neutron star system may be lower than the black hole case, owing to the stronger outflows in the former system.

It is generally believed that GRB 170817A originates from a binary NS merger. However, strictly speaking, the possibility of a light BH-NS merger isn’t ruled out. The serious argument against a BH-NS merger is that in this case the BH mass would be unusually low, \(\sim 1.4M_\odot\). In fact, a NS-mass BH may be present in relativistic binary systems because such binaries could result from collisions of primordial BHs with NSs (Abramowicz et al. 2018). In the BH-NS merger case, compact objects after the mergers are undoubtedly black holes, and therefore our slim disc model is also valid.

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