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Revisiting black hole hyperaccretion in the center of gamma-ray bursts for the lower mass gap

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ABSTRACT

The ultrarelativistic jets triggered by neutrino annihilation processes or Blandford-Znajek (BZ) mechanisms in stellar-mass black hole (BH) hyperaccretion systems are generally considered to power gamma-ray bursts (GRBs). Due to the high accretion rate, the central BHs might grow rapidly on a short timescale, providing a new way to understand " the lower mass gap" problem. In this paper, we use the BH hyperaccretion model to investigate BH mass growth based on observational GRB data. The results show that (i) if the initial BH mass is set as 3 $M_\odot$, the neutrino annihilation processes are capable of fueling the BHs to escape the lower mass gap for more than half of long-duration GRBs (LGRBs), while the BZ mechanism is inefficient on triggering BH growths for all LGRBs; (ii) the mean BH mass growths in the LGRB case are much larger than these in the case of LGRBs associated with supernovae (SNe) for both mechanisms, which imply that more massive progenitors or lower SN explosion energies prevail throughout LGRBs; (iii) for the short-duration GRBs, the mean BH mass growths are satisfied with the mass supply limitation in the scenario of compact object mergers, but the hyperaccretion processes are unable to rescue BHs from the gap in binary neutron star (NS) mergers or the initial BH mass being 3 $M_\odot$ after BH-NS mergers.

Keywords: accretion, accretion disks - black hole physics - gamma-ray burst: general - magnetic fields - neutrinos

1. INTRODUCTION

Gamma-ray bursts (GRBs) are the most luminous explosions in the universe. According to their durations, GRBs can be classified into two categories: short-duration GRBs (SGRBs; $T_{90} < 2$ s) and long-duration GRBs (LGRBs; $T_{90} > 2$ s) (Kouveliotou et al. 1993). SGRBs are generally believed to be produced by merger events of two compact objects, i.e., two neutron stars (NSs) or a black hole (BH) and an NS (e.g., Eichler et al. 1989; Narayan et al. 1992; Nakar 2007), and LGRBs are widely considered to originate from the collapse of massive stars (e.g., Woosley 1993; Woosley & Bloom 2006; Janka 2012). Moreover, some LGRBs are associated with Type Ib/c supernovae (SNe, see e.g., Hjorth et al. 2003; Malesani et al. 2004; Berger et al. 2011; Hjorth & Bloom 2012; Greiner et al. 2015), which sheds light on the progenitors and central engines of L-GRBs.

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Two popular models have been proposed for the central engines of GRBs, involving a rotating stellar-mass BH surrounded by a hyperaccretion disk (e.g., Paczyński 1991; Narayan et al. 1992; MacFadyen & Woosley 1999; Liu et al. 2017a) and a millisecond magnetar (e.g., Duncan & Thompson 1992; Usov 1992; Dai & Lu 1998a,b; Kluźniak & Ruderman 1998; Zhang & Mészáros 2001; Metzger et al. 2011). The GRB jets could be powered either by the rotational energy of the magnetars or by the gravitational or rotational energy of the accreting BHs. In the BH hyperaccretion scenario, neutrinos radiated from the heated disk matter can liberate the gravitational energy and then annihilate outside of the disk to produce GRB jets. This hyperaccretion mode is called neutrino-dominated accretion flows (NDAF, e.g., Popham et al. 1999; Narayan et al. 2001; Kohri et al. 2005; Gu et al. 2006; Chen & Beloborodov 2007; Kawanaka & Mineshige 2007; Liu et al. 2007; Lei et al. 2009; Xue et al. 2013). For a review see Liu et al. (2017a). Alternatively, the strong magnetic fields threading the BH horizon can also power the Poynting jets to efficiently extract the BH's rotational energy, namely, the Blandford-Znajek (BZ) mechanism (Blandford & Znajek 1977; Lee et al. 2000). In our work, we applied the neutrino annihilation process and BZ mechanism to investigate BH mass growth, and it is interesting to note that neutrino annihilation, as the initial dominant mechanism, could be replaced by BZ jets when the accretion rate decreases (e.g., Liu et al. 2017b, 2018).

In the hyperaccretion system, the BH mass and spin should undergo drastic evolution (e.g., Liu et al. 2015; Song et al. 2015). According to the GRB progenitor models, the initial BH mass is generally considered to approximately 3 $M_\odot$. Thus, the BH mass growth in the center of GRBs should be related to the lower mass gap (or the first mass gap) in the mass distribution of the compact objects. This gap (very few compact objects exist in the range of $\sim 2-5\ M_\odot$) was discovered in the statistical analyses of the X-ray binary observations (Özel et al. 2010; Farr et al. 2011).

Three $\sim 2\ M_\odot$ NSs were measured using the "Shapiro delay" effects (Demorest et al. 2010; Antoniadis et al. 2013; Cromartie et al. 2020). Recently, NASA's *NICER* constrained the mass measure of PSR J0740+6620, $2.072^{+0.067}_{-0.066}\ M_\odot$ (Miller et al. 2021; Riley et al. 2021). Furthermore, Thompson et al. (2019) reported a $\sim$ 3 $M_\odot$ BH candidate in a noninteracting low-mass binary system. In the aLIGO/Virgo detections, the compact remnants of GWs 170817 (Abbott et al. 2017) and 190425 (Abbott et al. 2020a) and one of the objects participating in GW 190814 (Abbott et al. 2020b) are all in the gap. one can find that a lower mass gap exists, but a small number of compact objects still remain here. Belczynski et al. (2012) proposed that the rapid explosion mechanism of core-collapse SNe (CCSNe) could absorb the newborn remnants from the gap. Liu et al. (2021a) simulated that the gap can be naturally built by the low explosion energy dominated distribution of CCSNe.

In this paper, by using a GRB sample, we revisit the BH hyperaccretion systems with a neutrino annihilation process and BZ mechanism and then analyze the effects of BH mass growth on the lower mass gap. This paper is organized as follows. In Section 2, we present the analytical models for describing the evolution of a Kerr BH and estimating the BH mass growth. The main results are shown in Section 3. Conclusions and discussions are made in Section 4.

2. MODEL

2.1. *BH evolution*

As a plausible central engine of GRBs, a rotating stellar BH surrounded by a hyperaccretion disk with a very high accretion rate should trigger violent evolution of BH characteristics. Based on the conservation of energy and angular momentum, the mass and angular momentum of the BH evolve with time as (e.g., Liu et al. 2012)

$$\frac{dM_{\rm BH}}{dt} = \dot{M} e_{\rm ms}, \tag{1}$$

$$\frac{dJ_{\rm BH}}{dt} = \dot{M} l_{\rm ms}, \tag{2}$$

where $M_{\rm BH}$ and $J_{\rm BH}$ are the mass and angular momentum of the BH, $\dot{M}$ is the mass accretion rate, and $e_{\rm ms}$ and $l_{\rm ms}$ are the specific energy and angular momentum corresponding to the marginally stable orbit radius of the BH. They are defined as $e_{\rm ms} = \frac{1}{\sqrt{3x_{\rm ms}}}\left(4-\frac{3a_*}{\sqrt{x_{\rm ms}}}\right)$ and $l_{\rm ms} = 2\sqrt{3}\frac{GM_{\rm BH}}{c}\left(1-\frac{2a_*}{3\sqrt{x_{\rm ms}}}\right)$, respectively, where $a_* \equiv cJ_{\rm BH}/GM_{\rm BH}^2$ $(0 \le a_* \le 1)$ is the dimensionless spin parameter of the BH and $x_{\rm ms}$ is the dimensionless marginally stable orbit radius of the disk, which is defined as $x_{\rm ms} = 3 + Z_2 - \sqrt{(3-Z_1)(3+Z_1+2Z_2)}$, where $Z_1 = 1 + (1-a_*^2)^{1/3}[(1+a_*)^{1/3} + (1-a_*)^{1/3}]$ and $Z_2 = \sqrt{3a_*^2 + Z_1^2}$ (e.g., Bardeen et al. 1972; Novikov 1998; Kato et al. 2008).

By combining Equations (1) and (2), the evolution of the BH spin can be expressed by (e.g., Hou et al. 2014)

$$\frac{da_*}{dt} = 2\sqrt{3}\frac{\dot{M}}{M_{\rm BH}}\left(1-\frac{a_*}{\sqrt{x_{\rm ms}}}\right)^2. \tag{3}$$

According to the above equations, we can obtain the time-dependent characteristics of the BH once the initial mass $M_{\rm BH,0}$ and spin $a_{*,0}$ of the BH are given. Here, $M_{\rm BH,0} = 3\ M_\odot$ and $a_{*,0}$=0.5 and 0.9 are adopted in the calculations.

2.2. *Two mechanisms*

The mean luminosity of the GRB jet $L_{\rm j}$ can be estimated as (e.g., Fan & Wei 2011; Liu et al. 2015)

$$L_{\rm j} \simeq \frac{(E_{\gamma,\rm iso} + E_{\rm k,iso})(1+z)\theta_{\rm j}^2}{2T_{90}}, \tag{4}$$

where $E_{\gamma,\rm iso}$ is the isotropic radiated energy in the prompt emission phase, $E_{\rm k,iso}$ is the isotropic kinetic energy powering long-lasting afterglow, z is the redshift, $\theta_{\rm j}$ is the half-opening angle of the jet, and T_{90} can be roughly considered as the duration of the violent activity of the central engine.

For a BH hyperaccretion system in the center of GRBs, the energy output given by Equation (4) is determined by the neutrino annihilation luminosity $L_{\nu\bar{\nu}}$ or the BZ jet power $L_{\rm BZ}$. The annihilation luminosity can be written as a function of the BH mass accretion rate and the

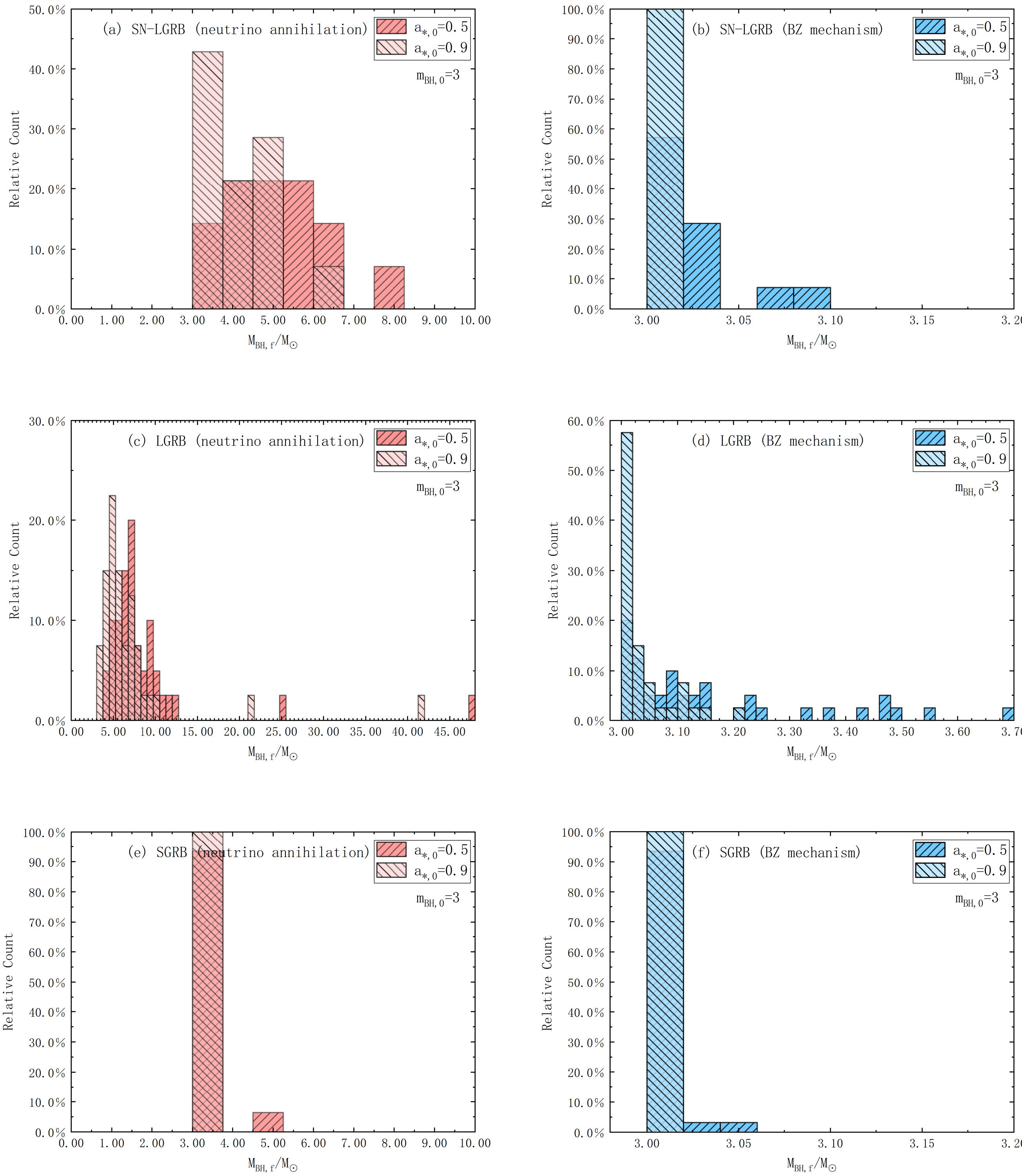

Figure 1. Distributions of the final BH mass $M_{\rm BH,f}$ for different GRB data and two different jet-launching mechanism. The red and blue bars correspond to the neutrino annihilation process and the BZ mechanism, respectively. The initial BH mass $M_{\rm BH,0}$ is 3 $M_\odot$. The dark and light colors denote the initial BH spin $a_{*,0} = 0.5$ and 0.9, respectively.

spin parameter a_* (Zalamea & Beloborodov 2011), i.e.,

$$L_{\nu\bar{\nu}} \approx 1.59 \times 10^{54}\ x_{\rm ms}^{-4.8}\ m_{\rm BH}^{-3/2} \times \begin{Bmatrix} 0 & \text{for } \dot{m} < \dot{m}_{\rm ign} \\ \dot{m}^{9/4} & \text{for } \dot{m}_{\rm ign} < \dot{m} < \dot{m}_{\rm trap} \\ \dot{m}_{\rm trap}^{9/4} & \text{for } \dot{m} > \dot{m}_{\rm trap} \end{Bmatrix} \text{erg s}^{-1}, \quad (5)$$

where $m_{\rm BH} = M_{\rm BH}/M_\odot$, $\dot{m} = \dot{M}/(M_\odot {\rm s}^{-1})$, $\dot{m}_{\rm ign}$ is the dimensionless critical ignition accretion rate, $\sim 0.001\ M_\odot\ {\rm s}^{-1}$, and $\dot{m}_{\rm trap}$ are the dimensionless accretion rates if neutrino trapping appears (e.g., Chen & Beloborodov 2007; Xue et al. 2013; Song et al. 2015).

The BZ jet power can be estimated by (e.g., Liu et al. 2018)

$$L_{\rm BZ} = 9.3 \times 10^{53} a_*^2 \dot{m} X(a_*)\ \text{erg s}^{-1}, \quad (6)$$

and

$$X(a_*) = F(a_*)/(1+\sqrt{1-a_*^2})^2, \quad (7)$$

where $F(a_*) = \left[\left(1+q^2\right)/q^2\right]\left[(q+1/q)\arctan(q)-1\right]$ with $q = a_*/(1+\sqrt{1-a_*^2})$.

3. RESULTS

We adopt the data of 14 LGRBs associated with SNe (hereafter SNe-LGRBs, Song & Liu 2019), 40 LGRBs with jet breaks (Yi et al. 2017), and 31 SGRBs (Liu et al. 2015) to calculate the BH mass growth in the BH hyperaccretion systems with neutrino annihilation processes and the BZ mechanism. The durations, redshifts, half-opening angles, $E_{\gamma,\rm iso}$, and $E_{\rm k,iso}$ are included.

In Figure 1, we demonstrate the final BH mass $M_{\rm BH,f}$ distributions for SN-LGRB, LGRB, and SGRB cases. The red and blue bars correspond to the neutrino annihilation process and the BZ mechanism, respectively. The dark and light colors denote the initial BH spin $a_{*,0}$ = 0.5 and 0.9, respectively. Since the accretion rate for the BZ mechanism can be significantly lower than that for the neutrino annihilation mechanism for the same output energy, it can be seen that the mass growth under the BZ mechanism is less efficient than neutrino annihilation for all GRB cases. In other words, the neutrino annihilation mechanism would be an easier way for a BH to escape the lower mass gap, especially for the long accretion timescale. Moreover, one can expect that a smaller initial BH spin parameter is favored for BH mass growth. Obviously, the mean jet luminosity is weaker for both lower accretion rates and lower BH spin values, as shown in Equations (5) and (6).

3.1. *SN-LGRB case*

The physical relation between SNe and LGRBs is firmly established with the accumulated evidence (e.g., Hjorth et al. 2003; Zhang et al. 2009), and it has been widely accepted that these SN-LGRB events are born out of the deaths of massive stars ($> 8\ M_\odot$). In the collapse phase of $\sim 20-40\ M_\odot$ progenitors, the core inevitably collapses to form a proto-NS and then continues to collapse into a BH ($\sim 3\ M_\odot$), creating a large amount of neutrinos. Neutrin irradiation revives the stalled shock launched at the core bounce and pushes off the remainder of the star, powering a CCSN (e.g., Zhang et al. 2008; Liu et al. 2021a, and references therein). Then, the fallback hyperaccretion on the central BH powers the ultrarelativistic jets. Once the jets break out from the envelope in the line-of-sight direction, a GRB can be observed. For the more massive progenitor stars ($> 40\ M_\odot$), the core directly collapses to form BHs and is generally larger than approximately $\sim 5\ M_\odot$ (e.g., Heger & Woosley 2002). Thus, we set $M_{\rm BH,0} = 3\ M_\odot$ to analyze the final BH mass distribution using the NS-LGRB sample.

Figures 1(a) and 1(b) show the distribution of the final BH mass after the accretion phase for 14 SN-LGRB events. For the BZ mechanism, the mean BH mass growths are about 0.023 $M_\odot$ for $a_{*,0} = 0.5$ and about 0.004 $M_\odot$ for $a_{*,0} = 0.9$, as shown in Table 1. For the neutrino annihilation process, the mean BH mass growths are approximately 2.113 and 1.079 $M_\odot$ for $a_{*,0}$ = 0.5 and 0.9, respectively. It is important to note that for $a_{*,0} = 0.5$ under the neutrino annihilation mechanism, there are more than 40 % LGRBs associated with SNe in which the BHs exceed the upper limit of the mass gap, $\sim 5\ M_\odot$, successfully.

It should be noted that there exists inevitable competition on matter and energies between SNe and LGRBs (e.g., Song & Liu 2019; Liu et al. 2021a). The SN energy depends on the initial explosion energy; however, the LGRB energy is related to the total fallback accretion mass. The typical luminosity (energy) of LGRBs associated with SNe is lower than that of LGRBs, which is reflected by the differences in the final BH mass distribution, as shown in Figures 1(a-d), and the values of the mean BH mass growths, as displayed in Table 1. Regardless, a hydrogen envelope-deficient environment is advantageous for both events, which can reduce the stress of the energy competition. Accordingly, a massive progenitor star with powerful stellar winds would be favored as a promising progenitor of the SN-LGRB case. Once the hydrogen envelope is retained in the collapsar mode, a jet breakout should occur within hundreds of seconds, and the corresponding accretion rate is lower than the

Table 1. Mean BH mass growths in all cases.

Case	$a_{*,0}$	Mechanism	Mean BH mass growth ($M_\odot$)	Figure
SN-LGRB	0.5	Neutrino annihilation	2.113	1(a)
SN-LGRB	0.9	Neutrino annihilation	1.079	1(a)
SN-LGRB	0.5	BZ	0.023	1(b)
SN-LGRB	0.9	BZ	0.004	1(b)
LGRB	0.5	Neutrino annihilation	5.845	1(c)
LGRB	0.9	Neutrino annihilation	4.069	1(c)
LGRB	0.5	BZ	0.161	1(d)
LGRB	0.9	BZ	0.036	1(d)
SGRB	0.5	Neutrino annihilation	0.227	1(e)
SGRB	0.9	Neutrino annihilation	0.062	1(e)
SGRB	0.5	BZ	0.003	1(f)
SGRB	0.9	BZ	0.001	1(f)

ignition of NDAFs. Then, the BZ jets monopolize the energy release. Nevertheless, for ultra-LGRBs associated with luminous SNe, such as GRB 111209A with SN 2011kl, only massive progenitors can support the ultra-long activity timescale of the hyperaccretion process and violent explosion, so $> 40\ M_\odot$ (even $\sim 70\ M_\odot$) progenitors are inescapably required (e.g., Nakauchi et al. 2013; Liu et al. 2018; Song & Liu 2019).

3.2. *LGRB case*

Figures 1 (c) and (d) display the distribution of the final BH mass for LGRBs. As shown in Figure 1(c), the BH mass has no significant increase in the BZ mechanism for $a_{*,0} = 0.9$, with 80 % of LGRBs growing within 3.1 $M_\odot$ and the rest growing to approximately 3.2 $M_\odot$. For a smaller initial BH spin parameter $a_{*,0} = 0.5$, 50 % of LGRBs shows growth lower than 0.1 $M_\odot$, while the rest can gain a mass increment between 0.1 and 0.7 $M_\odot$. In contrast, the mass growth in the neutrino annihilation mechanism in Figure 1 (d) is much more promising, with many LGRBs successfully closing the lower mass gap. For the faster initial spin $a_{*,0} = 0.9$, the success rate is approximately 65 %, while for the slower spin $a_{*,0} = 0.5$, the success rate reaches 88 %. Additionally, there are some extreme cases in which the final BH mass increases to tens of solar masses.

For LGRBs, the absence of associated SNe is either caused by the explosion energy being too weak, or too distant to be observed. Overall, the typical energy of LGRBs is higher than that of LGRBs associated with SNe, which implies that more massive or lower metallicity stars are LGRB progenitors or that lower explosion energy is more prevalent for LGRB progenitors. Moreover, the mean BH mass growths are about 5.845 and 4.069 $M_\odot$ for $a_{*,0} = 0.5$ and 0.9, respectively, as shown in Table 1 when the neutrino annihilation process is dominant; for the BZ mechanism, the mean growths are about 0.161 and 0.036 $M_\odot$ for $a_{*,0} = 0.5$ and 0.9, respectively.

Since the accretion rate decreases with time, $\dot{M} \sim t^{-5/3}$, in the fallback accretion phase, neutrino annihilation process lasting tens of seconds should be replaced by the BZ mechanism (e.g., Liu et al. 2021a; Wei et al. 2021), and the BH mass growth might be slightly less than the above maximum values.

3.3. *SGRB case*

Since the maximum mass of NSs constrained by the recent observations, such as GW 170817 and *NICER* PSR J0030+0451, is about 2.4 $M_\odot$ (e.g., Li et al. 2020, 2021, and references therein), the coalescence of two NSs is hardly to produce a $> 5\ M_\odot$ BH but creates a BH in the lower mass gap and the following multimessenger signals. As an extreme example, in the merger of a massive NS, $\sim 2\ M_\odot$, and a BH, the accretion mass could reach $\sim 0.8\ M_\odot$ constrained by the SGRB extended emissions (e.g., Liu et al. 2012). Thus, one can expect that the BHs in the center of SGRBs cannot grow up to break through the lower mass gap if the initial accreting BH mass is set to 3 $M_\odot$ after mergers.

For the BH hyperaccretion system born after the merger of two compact objects, the merger ejecta hardly stops the SGRB jets, but the limited accretion matter can support no more than seconds of the central engine activity. The distributions of the final BH mass of SGRBs are shown in Figures 1(e) and 1(f). If the ultrarelativistic jet is powered by the BZ process, for both initial BH spin parameters, one can see that the growth within 0.05 $M_\odot$. Meanwhile, the mean BH mass growths are approximately 0.003 and 0.001 for $a_{*,0} = 0.5$ and 0.9, respectively. If the neutrino annihilation process is dominant, although BHs with initial BH spin parameter $a_{*,0} = 0.9$ still fill in the gap, there is almost no chance for BHs with the initial BH spin parameter

$a_{*,0} = 0.5$ to escape the gap. Furthermore, the mean BH mass growths are approximately 0.227 and 0.062 for $a_{*,0} = 0.5$ and 0.9, respectively. Only two SGRBs whose central BHs grow from 3 $M_\odot$ to ~ 5 $M_\odot$ with $a_{*,0} = 0.5$, which is impossible in the merger scenario, and the BZ mechanism should be reasonable for their engines.

Thus, the NS-NS mergers can contribute a small amount of $2 - 5$ $M_\odot$ BHs, and the contribution of the BH-NS mergers is determined by the initial BH mass. Fortunately, the merger events are much fewer than the collapse events (e.g., Podsiadlowski et al. 2004), and a lower mass gap is not empty but should exist.

4. CONCLUSIONS AND DISCUSSION

In this paper, we calculated the BH mass growth using the BH hyperaccretion model and observational GRB data to investigate the contribution of hyperaccretion to lower mass gap formation. If BH hyperaccretion is considered the central engine of LGRBs, the mass of most LGRB progenitors is limited to $20 - 40$ $M_\odot$, which corresponds to the theoretical initial BH mass in the lower mass gap. As a result, one can notice that these newborn BHs could grow up and break away from the gap if the neutrino annihilation process is dominated, even just in the initial accretion phase. For the SN-LGRB case, we propose that the newborn BHs in the center of CCSNe with lower initial explosion energy have large probabilities of escaping from the gap. Of course, for progenitors without hydrogen envelopes or a low-metallicity progenitor mass larger than 40 $M_\odot$, the BH might grow enough or be naturally larger than 5 $M_\odot$. For the SGRB case, the BHs born in NS-NS mergers have no chance to escape from the gap, but those in BH-NS mergers are probably if the difference between the initial accreting BH mass and the upper limit of the gap is less than ~ 1 $M_\odot$.

Mass outflows might occur in the BH hyperaccretion system, which will participate in nucleosynthesis to power kilonovae or SNe in merger or collapsar scenarios (e.g., Surman et al. 2011; Song et al. 2018; Song & Liu 2019; Liu et al. 2021b). Once the effects of outflows are considered, the above results on the values of the BH mass growths should be their upper limits. Whatever, the hyperaccretion mode is the only way to significantly influence the BH evolution and the mass distribution of compact objects for the single stars.

The ultrarelativistic jets are distinctly unobservable if they are out of sight or choked in the envelopes or circumstances. Therefore, the GRB sample in our work can only partially represent the contribution of the hyperaccretion process to the lower mass gap. Nevertheless, jets, disks, and explosions are still strong sources of MeV neutrinos and gravitational waves (e.g., Liu et al. 2016, 2017b; Wei et al. 2019; Wei & Liu 2020), and one can expect further joint multimessenger observations to describe the shape of the lower mass gap.

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