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LGRBs Born in Ultra-compact Binary System: Companion's Long-term Tidal Force and Periodicity in GRB Afterglows

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Abstract

Most massive stars reside in binary or multi-object systems. Short gamma-ray bursts (sGRBs), the product of the merger of double compact objects, may originate from massive common-envelope binaries. In contrast, the progenitors of long GRBs (lGRBs) are typically considered isolated massive stars. However, no effective method has yet been established to identify potential companions from current observations. Recent studies have demonstrated that quasi-periodic oscillation signatures can serve as a promising tool to probe the properties of GRB central engines. In this study, by drawing an analogy to periodicity in X-ray binaries, we explore the precession periods of companion-induced disk precession for lGRBs born in the ultra-compact binary scenario. Our results suggest that the periodicity observed in lGRB afterglows, measured in units of 1000 s or more, may indicate that lGRBs originate within binary systems. GRB 050904 could represent a rare case where the burst occurred in a binary system, leaving behind a black hole–black hole binary at redshift $z = 6.29$.

Key words: (stars:) gamma-ray burst: general – (stars:) binaries (including multiple): close – accretion, accretion disks

1. Introduction

Gamma-ray bursts (GRBs), the most luminous electromagnetic bursts, are believed to result from the catastrophic death of stars. Short GRBs (sGRBs), which are linked to the merger of double compact objects, are considered as the most promising electromagnetic counterparts to gravitational waves (GWs; Abbott et al. 2017a). Long gamma-ray bursts (lGRBs) are thought to arise from the collapse of massive single stars and are often linked to Type Ib/c supernovae (SNe; Hjorth et al. 2003; Stanek et al. 2003). However, only a subset of Type Ib/c SNe is associated with lGRB production, suggesting that lGRBs originate from a rare or distinct progenitor channel (Berger et al. 2003; Podsiadlowski et al. 2004). Three requirements are suggested for the formation of lGRBs: the star must be massive enough to collapse, it must rotate rapidly to form a disk, and its hydrogen or even helium envelope must be stripped to allow the jet through the stellar shell. Most massive stars are thought to reside in binary or multi-object systems (Sana et al. 2012; Duchêne & Kraus 2013). In a binary system, massive stars can attain high rotation rates by accreting material from a companion (Cantiello et al. 2007). This accretion is crucial for stripping the hydrogen and helium envelopes of lGRB progenitors at high redshift. Because massive stars at high redshift typically have lower metallicities, their stellar winds are too weak to remove their outer layers. Identifying such ultra-compact binaries from SNe, GRBs, or GW events is crucial for understanding the evolution of multiplicity (e.g., Abbott et al. 2017c). Two exotic thermal components were identified in ultra-long GRB 101225A (Thöne et al. 2011). The hotter component has a temperature $T \sim 10^7$ K and a radius $r \sim 2 \times 10^{11}$ cm, while the cooler component has a temperature $T \sim 10^4$ K and a radius $r \sim 2–7 \times 10^{14}$ cm. A merger of a common-envelope helium star and a neutron star (NS) was proposed to explain these observations, where both thermal components are attributed to the interaction of the GRB jet with the ejected common-envelope material (Thöne et al. 2011). A hotter component was also observed in the SN-associated GRB 090618, and a model involving the sequential collapse of two stars in a binary was tested for this GRB (Izzo et al. 2012). Zou et al. (2021c) proposed that the companion star may obscure the light from the GRB jet when it is aligned with the jet's orientation. The discovery of a 12.4 days period in the multi-band light curves of Type Ic SN 2022jli confirms that the collapse of massive stars can occur in the close binary phase (Chen et al. 2024).

The X-ray plateau and X-ray flare are two types of signatures that record the long-lasting central engine of GRBs (Dai & Lu 1998; Zhang & Mészáros 2001; King et al. 2005; Perna et al. 2006; Zheng et al. 2021). Such long-lasting activities open a crucial window to insight into the central engine of GRBs. Possible quasi-periodic oscillation (QPO) signatures have been identified in prompt emissions or X-ray afterglows and are used to distinguish GRBs with a black hole (BH) origin (Zheng et al. 2024) or a magnetar origin (Zou et al. 2021a;

Chirenti et al. 2023; Xiao et al. 2024; Zhang et al. 2024). However, some of the reported QPO signals contain only of about five periods, with a high likelihood of being accidental. GRB 050904, which may exhibit ten periods, is believed to originate from the precession of a tilted disk surrounding a Kerr BH (Zheng et al. 2024). Such an explanation requires that both the angular momentum of the central BH and the precession radius of the disk remain constant or that they are in a very delicate balance. Intriguingly, the disk precession arising from the Lense-Thirring effect with a time-evolving periodicity during the early disk formation phase has been suggested by both semi-analytical analysis (Stone et al. 2013) and numerical simulations (Dyda & Reynolds 2020). Such a time-evolving periodicity may have been observed in the X-ray binary (Stella & Vietri 1998) and the accreting supermassive black hole (Masterson et al. 2025). Recently, a time-evolving periodicity identified in the GRB prompt emission was also suggested to originate from the Lense-Thirring effect (Zheng et al. 2025, submitted). In this context, a more natural model to explain the constant periodicity in GRB 050904 is expected. In this study, we discuss lGRBs originating from a binary system, where the companion's long-term tidal force acts on the disk, inducing superorbital disk precession. The disk-slaving jet, powered by a long-lasting central engine, characterizes constant periodicity and causes a QPO-modulated light curve with a period exceeding the orbital period by an order of magnitude. The study is organized as follows. In Section 2, we revisit the long-lasting central engine of GRBs and their observational characteristics. Section 3, we explore the physical process of companion-induced disk precession, discuss three different formation channels for the central engine, and apply this scenario to the observed periodicity in GRB 050904. The summary and the discussion are given in Section 4.

2. Long-lasting GRB Central Engines

Two types of compact objects, magnetars and BHs, are believed to serve as the central engines of GRBs. The magnetic dipole radiation-driven collimated jet from a magnetar is widely accepted for accounting for the observed plateau in the X-ray afterglow of GRBs (e.g., Dai & Lu 1998; Zhang & Mészáros 2001). The power of this magnetic dipole radiation is given by $L_{\rm MD} = B_s^2 R^6 \Omega^4 (1 + \sin^2\theta)/6c^3$ (Spitkovsky 2006), where B_s is the magnetar surface magnetic field strength, Ω is the angular frequency of magnetar's spin, R is the radius of the magnetar, θ is the angle between the rotation axis and the magnetic dipole moment, and c is the speed of light. The observed luminosity of this long-lasting activity typically exhibits a plateau followed by a rapid decay, that is

$$L_{\rm obs,m} = \eta_e \eta_X L_0 \left(1 + \frac{t}{T_b}\right)^{\alpha}, \quad (1)$$

where η_e is the radiation efficiency, and considering the jet could be a Poynting dominant flow powered by magnetic field, we suggest this value should be close to 1 (e.g., Zhang et al. 2007; Wang et al. 2015). η_X is the energy fraction into the detector window; the popular value for the Swift X-ray Telescope (Swift/XRT) is 0.1–0.3 (e.g., Zou et al. 2021b). $L_0 = L_{{\rm MD},t=0}$ is the power of magnetic dipole radiation at the GRB trigger time. T_b is the characteristic spin-down timescale. Typically, B_s is regarded as the constant, while Ω is considered to decrease as the energy dissipation. If the observed radiation originates from energy injection into the forward shock, the temporal information of the central engine activity may be lost during the energy injection process. To retain signatures of central engine activity, we prefer that the observed electromagnetic radiation originates from internal dissipation. In this case, the typical decay slope is $\alpha \sim -2.0$. When the central magnetar undergoes a catastrophic collapse into a BH, the jet is expected to cease at the moment of collapse, corresponding to the observed X-ray luminosity, which exhibits a plateau followed by a sharp decay ($\alpha < -3$; e.g., Troja et al. 2007; Lyons et al. 2010).

The magnetar collapse scenario is widely accepted as an explanation for the observed X-ray afterglow, which is characterized by a plateau followed by a sharp decay. However, the QPO signature observed in the X-ray afterglow of GRB 050904, which begins during the plateau phase and continues into the sharp decay, does not support this hypothesis, instead suggesting an origin from a Kerr BH (Zheng et al. 2024). Such a scenario refers to a Blandford–Znajek (BZ) mechanism (Blandford & Znajek 1977) powered jet (referred to as a BZ jet). The dimensionless spin parameter of a Kerr BH is written as $a = {\rm c}J_{\rm BH}/{\rm G}M_{\rm BH}^2$, where $J_{\rm BH}$ represents the BH angular momentum, $M_{\rm BH}$ is the BH mass, and G is the gravitational constant. The power of BZ jet is expressed as $L_{\rm BZ} \approx \frac{kf}{4\pi {\rm c}} \Phi_{\rm H}^2 \Omega_H^2$, where $k \approx 0.05, f \approx 1$ for a large a close to 0.95 (Tchekhovskoy et al. 2011). The magnetic flux passing through the BH horizon is expressed as $\Phi_{\rm H} \sim \pi r_H^2 B_H$, and the angular frequency of the BH horizon is given by $\Omega_H = ac/2r_H$, where the radius of the outer horizon is given by $r_H = {\rm G}M_{\rm BH}(1 + (1 - a^2)^{1/2})/c^2$. During the merger of two compact objects or the collapse of a massive star, the magnetic field can also be dragged into the newborn remnant, as the magnetic field line is frozen into the material. If the remnant is a BH, then the magnetic field lines are expected to diffuse out of the BH naturally, as the BH no-hair theorem predicts that a BH has no capability to possess a magnetic field. However, when the material possesses enough angular momentum, it forms a disk, and the diffusing magnetic field would be squeezed by the infalling disk. In the early phase, the disk may exhibit a rather high mass accretion rate, which can compress the magnetic flux at the BH horizon. The magnetic flux $\Phi_{\rm H}$ remains constant during this phase, i.e., $\Phi_{\rm H} \propto t^0$

(Tchekhovskoy & Giannios 2015). As the mass accretion rate decreases, the magnetic pressure pushes the disk to a larger radius. In this process, the $\Phi_{\rm H}$ decreases rapidly as the mass accretion rate declines, following $\Phi_{\rm H} \propto \dot{M}^{4/3}$. The mass accretion rate decreases with time as $\dot{M} \propto t^{-5/3}$. Finally, the observed luminosity of the BZ jet can be expressed as (Kisaka & Ioka 2015; Zheng et al. 2024)

$$L_{\rm obs,BH} \approx \eta_e \eta_X L_{\rm BZ,0}\left(1 + \frac{t}{t_b}\right)^{-40/9}, \tag{2}$$

where $L_{\rm BZ,0} = \frac{\pi c}{320} r_H^2 B_{\rm H,0}^2$ is the characteristic luminosity, t_b is the characteristic timescale representing the diffusion of the magnetic field out of the BH horizon, and the characteristic magnetic field strength $B_{\rm H,0}$ corresponds to a scenario in which the magnetic field is compressed at the BH horizon (Zheng et al. 2024).

3. Companion Tidal Force and QPO-modulate lGRB Afterglows

3.1. Companion-induced Disk Precession

The tidal force of the companion star acting on an accretion disk in a close binary system has been studied (e.g., Larwood 1997; Papaloizou & Pringle 1977). Such a disk characterizes rigid body precession and is accepted to explain the observed days-long QPO signature in X-ray binaries (e.g., Larwood 1998). The complex multi-pulse structure displayed during the prompt phase of GRBs may originate from an exotic "gamma-ray binary" with a precessing jet (Portegies Zwart et al. 1999). To explain the seconds-scale periodicity, Portegies Zwart et al. (1999) proposed a binary system consisting of a BH and an NS separated by 42 km, where the NS loses 80% of its mass, fueling a bright GRB. At the time of the GRB outburst, the distance between the NS and the BH had increased to 135 km. We cannot exclude the possibility that some GRBs originate from such exotic physical channels. However, given that lGRBs are typically associated with massive stellar collapse, we focus on a more general scenario: the progenitors of lGRBs, ultra-stripped Wolf-Rayet stars, reside in binary systems. As the primary star collapses, a compact central engine surrounded by an accretion disk is formed. The long-term tidal force from the companion induces the disk to precess, and the precession period can be written as (Larwood 1998)

$$P_{\rm pre} = \frac{7}{3} P_{\rm orb} \frac{(1+q)^{1/2}}{q \quad \cos\nu} \left(\frac{R_b}{r_{\rm disk}}\right)^{3/2} \tag{3}$$

where $P_{\rm orb}$ is the orbital period of the binary stars, $q = M_s/M_c$ is the mass ratio of the companion star and the central compact remnant, ν is the angle between the disk and the orbital plane of the companion star, R_b is the separation of two stars, $r_{\rm disk}$ is the radius of the newborn disk. The average separation of an elliptical orbit is given by $\bar{R}_b = a(1-e^2)^{1/2}$ (Martin et al. 2011). The disk radius is limited by the Roche radius R_R, one written as $r_{\rm disk} = \beta R_R$, where $\beta \sim 0.86$ for $0.03 < q < 2/3$, and $\beta = 1/(1 + \ln(1.8q)^{0.24})$ for $2/3 < q < 20$ (Paczynski 1977; Larwood 1998) and $R_R = 0.49a/(0.6 + q^{2/3}\ln(1+{\rm q}^{-1/3}))$ (Eggleton 1983).

The long-lasting activity signal observed in GRB afterglows is likely the result of a collimated jet. Due to the interaction between the precessing disk and the collimated jet, the jet precesses along with the disk. The angle between the orientation of the precessing jet $\boldsymbol{r}_{\rm jet}$ and the observer's line of sight $\boldsymbol{r}_{\rm obs}$ is given by (e.g., Zheng et al. 2024)

$$\begin{aligned}\cos(\psi(t)) &= \boldsymbol{r}_{\rm obs}\cdot \boldsymbol{r}_{\rm jet}\\ &= \cos(\theta_{\rm jet})\cos(\theta_{\rm obs}) + \sin(\theta_{\rm jet})\\ &\quad \times \sin(\theta_{\rm obs})\cos(2\pi t/P_{\rm pre} + \phi),\end{aligned} \tag{4}$$

where $\theta_{\rm jet}$ and $\theta_{\rm obs}$ represent the angles from the precession axis to the jet and to the observer, respectively. ϕ is the initial phase angle between the jet and the observer. The observed light curve is modulated by the evolution of angle ψ, known as the Doppler effect, and is given by $F(\psi) = D^3 F_{\psi=0}$, where the Doppler factor has $D = (1-\beta)/(1-\beta\cos(\psi))$, $\beta = (1 - 1/\Gamma^2)^{1/2}$, with Γ being the Lorentz factor of jet. Thus, the observed light curve would exhibit a QPO signature with a period corresponding to the disk precession. These superorbital periods are typically a factor of 10 or more longer than the binary orbital period. The observable activities in GRB afterglows generally last thousands to tens of thousands of seconds. Thus, for multiple cycles to appear in the GRB afterglow, the preferred post-explosion orbital period should be at most hundreds of seconds. Numerical simulations have confirmed such short periods (e.g., Becerra et al. 2019). For longer orbital periods, a bump in the light curve is expected (e.g., GRB 121027A; Wu et al. 2013).

3.2. Binary System in the Post-explosion Phase

BHs or magnetars are believed to survive the core collapse of massive stars and serve as the central engines of GRBs. Some lGRBs at low redshift have been confirmed to be associated with Type Ib/c SNe (Hjorth et al. 2003; Stanek et al. 2003). Two processes, the bounce from the proto-NS and the acceleration from neutrinos, may power the stellar shell to become the SN ejecta (Bethe & Wilson 1985; Janka et al. 2007). Whether the ejecta occurs can significantly affect the binary orbit at the post-explosion phase. Here, we discuss three physical scenarios in which a magnetar or BH survives the core collapse of a massive star. (A) The massive star directly collapses to a BH,[4] with part of

[4] A massive star collapsing into a BH may occur in a star with an initial mass $M_{\rm zero} > 25 M_\odot$ (Fryer et al. 2002; Woosley et al. 2002). Furthermore, the rotation rate, wind mass loss, and metallicity could also affect the final fate, determining whether the outcome is a magnetar or a BH (O'Connor & Ott 2011; Song & Liu 2023). Some studies suggest that the compactness of the presupernova stellar core ($\xi_{2.5}$) may serve as an indicator of whether the collapse of the stellar core leads to a successful explosion or forms a BH (O'Connor & Ott 2011; Ugliano et al. 2012; Sukhbold & Woosley 2014).

the shell forming the disk. In this scenario, the outer shell neither undergoes a bounce from the proto-NS nor is accelerated by neutrinos, and thus lacks the associated SN. One notable property is that the orbit may remain largely unchanged, with a constant circular orbit before and after the explosion phase. (B) The massive star undergoes a two-step collapse process. A massive magnetar forms in the first collapse. As it spins down or accretes to the critical mass, it collapses into a BH. In this scenario, part of the shell is ejected with ejecta mass ΔM, while the remaining mass aligns with the maximum mass of an NS, approximately $\sim 2.5\,M_{\odot}$ (e.g., Ai et al. 2023). Due to the bounce from the proto-NS and the acceleration from neutrinos, the associated SN is expected. Part of the shell forms a disk, and the orbital radius of the binary system increases significantly as the outer shell of the star is ejected. The distribution of SN-kick velocities is believed to be bimodal, with the lower component may represent SNe born in binary systems. The distribution of SN-kick velocities for NSs in binary systems can be well fitted with a Beta distribution, with a mean of $97\,\mathrm{km\,s^{-1}}$ (O'Doherty et al. 2023). In this study, to obtain a periodic light curve in the afterglow, the orbital separation of the binary is of about 10^{10} cm, corresponding to a relative speed between the two stars ranging from $10^{3}\,\mathrm{km\,s^{-1}}$ to $10^{4}\,\mathrm{km\,s^{-1}}$. Therefore, the SN-kick is negligible compared to the relative speed of the binary stars, and it can be more easily understood using Equation (5) in Abbott et al. (2017c). In this scenario, maintaining the binary in a bound state requires a low ejecta mass. Thus, we neglect the random SN-kick and assume that the escape of the ejecta is instantaneous. The binary system with an initial mass $M_0 = M_s + M_c + \Delta M$ and an initial semimajor axis a_i. The post-explosion semimajor axis a_f is the function of ejecta mass ΔM and orbital separation r at the explosion time, i.e., $a_f/a_i = (M_0 - \Delta M)/(M_0 - 2a_i\Delta M/r)$ (Hills 1983). The post-explosion orbital period is given by $P_{\rm orb} = 2\pi(a_f^3/G(M_0 - \Delta M))^{1/2}$. (C) The massive star collapses into a magnetar without a secondary collapse, with both the disk and SN expected. The properties are similar to those of context B, but a central engine with a lower mass is anticipated (e.g., Abbott et al. 2017b).

We explored six binary systems across the three physical scenarios outlined above, and the derived periods of disk precession are presented in Table 1. To obtain the lower limit of the precession period for each scenario, a compact object, an NS or a BH, as the companion star, is more reasonable, as also suggested by Fryer et al. (2014). For a CO core progenitor with a mass of about $5M_{\odot}$, the radius of its CO core is approximately $\approx 3\times10^{9}$ cm. A smaller radius, around $\sim 10^{9}$ cm, for the CO core was also suggested by Becerra et al. (2019). In this context, we adopt an initial orbital separation of $r = 5\times10^{9}$ cm for all cases. Table 1 shows that scenario A has the shortest disk precession period, one as short as 500 s. For scenarios B and C, this limit extends to 2000 s.

3.3. Periodicity in the X-ray Afterglow of GRB 050904

The X-ray afterglow of GRB 050904 has been suggested to exhibit periodicity, with the QPO-modulated internal plateau and subsequent sharp decay, which was thought to originate from a Kerr BH (Zheng et al. 2024). If the periodicity arises from the Lense-Thirring effect, as described by Zheng et al. (2024), the measured rest-frame period of 771 s suggests a precession radius of $r_{\rm BP} = 10^{8}$ cm for the accretion disk, assuming a BH mass of $M_{\rm BH} = 3\,M_{\odot}$ and a dimensionless spin parameter of $a \sim 1$. However, a potential issue is the constant periodicity, which requires both the angular momentum of the central BH and the precession radius of the disk to remain constant or to be in a very delicate balance. The semi-analytical calculation (Stone et al. 2013) and numerical simulation (Liska et al. 2018) suggest that the accretion disk precession period may increase during the early stages of disk formation. In contrast, a periodicity originating from companion-induced disk precession is likely more reasonable, as it heavily depends on the orbital parameters of the binary system and evolves slowly. As shown in Table 1, only the physical channel of Scenario A can explain the 771 s period in the afterglow of GRB 050904. In this case, the progenitor star directly collapsed into a BH at the time of the GRB eruption. This supports the argument presented by Zheng et al. (2024). Therefore, GRB 050904 could represent a rare case in which the GRB occurred in a binary system with an initial orbital separation of about 7×10^{9} cm, resulting in a BH-BH binary at redshift $z = 6.29$ (Kawai et al. 2006).

4. Summary and Discussions

Given that the majority of massive stars are observed to exist in binary or multi-object systems Sana et al. (2012), it is expected that lGRBs should predominantly originate from binary systems. However, a reliable method for identifying potential companions from observations is still lacking. Previous studies have suggested that exotic thermal components in the GRBs prompt emissions may provide evidence for the binary origin of lGRB progenitors (Thöne et al. 2011; Izzo et al. 2012). The detection of potential QPO signatures in both prompt and afterglow emissions reveals that the properties of the central engine are imprinted on the long-lasting activity signal. The days-long periodicity observed in X-ray binaries has been attributed to the long-term tidal effects of the companion star on the disk (e.g., Larwood 1998). Magnetars or BHs within accreting disks are typically considered the central engine configurations for GRBs, with potential companion stars often neglected. In this study, we explore the precession periods of companion-induced disk precession for lGRBs born in the ultra-compact binary scenario. Our results show that the precession period can be as short as hundreds of seconds. Thus, the QPO signatures observed in lGRB afterglows may originate from the companion-induced disk precession, e.g.,

Table 1
lGRBs Born in the Binary Systems and Disk Precession

Channel	M_p^{a} ($M_\odot$)	M_s ($M_\odot$)	ΔM ($M_\odot$)	R_R (10^9 cm)	$r_{\rm disk}$ (10^9 cm)	$e_{\rm post}^{b}$ -	$P_{\rm pre}$ ($\times$100 s)	T_c (yr)	$D_{\rm off}$ (kpc)
A	10.0	20.0	0	1.60	1.09	0	6.98	296	⋯
	10.0	10.0	0	1.89	1.41	0	4.74	888	⋯
B	5.00	3.50	2.50	2.05	2.12	0.417	22.4	2.92×10^4	0.24
	5.00	2.50	2.50	2.20	2.82	0.500	21.6	9.09×10^5	0.69
C	3.00	1.70	1.40	2.14	2.39	0.424	24.2	1.80×10^6	1.00
	3.00	1.20	1.40	2.30	3.23	0.500	22.0	5.29×10^6	2.58

Notes. The initial orbital separation $r = 5 \times 10^9$ cm and angle $\nu = 0$ are adopted for all cases, and the random SN-kick is neglected. We assuming the initial binary system with circular orbit.
[a] M_p is the mass of primary star at the time of core collapse.
[b] $^{(b)}$ The post-explosion ellipticity is given by $e_{\rm post} = \Delta M/(M_s + M_c)$.

GRB 050904. If the companion star is a stellar core or a massive NS, and the ejecta is sufficiently slow and massive, the two stars in the binary system will likely collapse sequentially within 10^2–10^3 s, forming a binary-driven hypernova (BdHNe) associated with the lGRB, as suggested by Fryer et al. (2014).

A binary system that survives twice core-collapse supernova explosions could also be the progenitor of a double compact object merger (for a review, see Berger 2014). After the second explosion, the coalescence timescale of the two compact objects can be written as (using circular orbits as an approximation) $T_c = \frac{5c^5(P_{\rm orb}/\pi)^{8/3}}{256(G\mathcal{M})^{5/3}}$, where chirp mass has $\mathcal{M} = (M_c M_s)^{3/5}/(M_c + M_s)^{1/5}$ (Postnov & Yungelson 2014). We display the coalescence timescale T_c in the penultimate column of Table 1. The results show that physical channel A has the shortest coalescence timescale, on the order of at least 100 yr. The physical channel C has the longest coalescence timescale, on the order of millions of years, and is associated with the lower limit of the delay time between double NS mergers and star formation activity (Berger 2014). In this study, the actual orbital velocity of the binary stars is as large as several 10^3 km s^{-1}. The ejecta of the explosion can carry away a portion of the momentum from the binary system. Assuming that the ejecta is symmetric with respect to the progenitor, the momentum of the ejecta can be written as $v_e \Delta M$, where v_e is the orbital velocity of the main star at the time of collapse, it is given by $v_e = (G/(a_i M_0))^{1/2} M_s$. This results in the binary system acquiring considerable momentum in the opposite direction, i.e., $v_b(M_0 - \Delta M) = v_e \Delta M$, where v_b is the bulk velocity of the binary system post-explosion. By combining the motion velocity of the binary system with the derived coalescence timescale, we can estimate the position of the merger event, also known as the offset distance for sGRBs. The derived offset distance is shown in the last column of Table 1. For channel C, which corresponds to the birth of sGRBs, the offset distances are approximately 1 kpc. Assuming the initial mass and the ejecta mass from the last row of Table 1, and an orbital separation of 10^{10} cm, the given offset distance is 29 kpc, and the corresponding motion velocity is 338 km s^{-1}. Such an offset distance is consistent with the results observed in sGRBs (Berger 2014).

In this study, we require an initial orbital separation $r \sim 10^{10}$ cm to ensure a short period. However, the population synthesis of binary systems remains uncertain, and the detailed distribution of r is poorly understood. BdHNe is a class with a progenitor system similar to the one introduced in this study. It requires a CO-NS binary progenitor with $r \lesssim 10^{11}$ cm, and the collapse of the CO core produces a suitable ejecta to trigger the collapse of the NS (Fryer et al. 2015). The binary in our model requires a shorter separation distance but imposes no limit on the type of companion, whether NS or BH, nor on the ejecta. Therefore, we consider that these two events have similar event rates. The local event rates of high-luminosity (HL) lGRBs and HL lGRBs born in BdHNe are estimated to be $\sim$1 Gpc^{-3} yr^{-1} (Sun et al. 2015) and $\sim10^{-2}$ Gpc^{-3} yr^{-1} (Fryer et al. 2015), respectively. In this context, we estimate that about $\sim$1% of HL lGRBs are born in such ultra-compact binaries. Considering the existence of low-luminosity lGRBs, we might expect that about ten cases have been observed by Swift/XRT, which has observed 1660 GRBs as of 2025 April 13.[5] Considering that only a small fraction of central engine long-term activity is characterized by internal plateaus, and that the number of higher-mass stars is lower, the fraction of GRB 050904-like events would be an order of magnitude lower, i.e., $\sim$0.1%. Therefore, the observation of GRB 050904 is indeed a rare event.

[5] https://www.swift.ac.uk/xrt_live_cat/#tableDiv

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