

Simulating the late stages of WD-BH/NS mergers: an origin for fast X-ray transients and GRBs with periodic modulations

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ABSTRACT

Recent studies indicate that mergers of a white dwarf (WD) with a neutron star (NS) or a stellar-mass black hole (BH) may be a potential progenitor channel for certain merger-kind, but long-duration γ -ray bursts (GRBs), e.g., GRBs 230307A and 211211A. The relatively large tidal disruption radius of the WD can result in non-negligible residual orbital eccentricity ($0 \lesssim e \lesssim 0.2$), causing episodic mass transfer, i.e., repeated tidal disruptions (RPDs) of the WD. We perform smoothed-particle-hydrodynamics simulations of RPDs in sixteen WD-BH/NS systems, capturing the subsequent mass transfer and accretion. The WD undergoes RPDs near the orbital periastron, modulating the ensuing accretion process, leading to variations of the accretion rate on the orbital period. Across all simulations, the peak accretion rates range from 4×10^{-4} to $0.2 M_{\odot} \text{ s}^{-1}$, while the RPD duration spans from ~ 10 s to an hour. More compact systems, i.e., those with a higher mass ratio (higher WD mass and lower accretor mass), tend to undergo fewer RPD cycles, resulting in shorter durations and higher accretion rates. If such events can launch relativistic jets, three categories of non-thermal X/ γ -ray transients are predicted, in decreasing order of their mean accretion rates: (1) an X-ray transient with a simultaneous GRB, both lasting for 10^{1-2} s; (2) a longer X-ray transient lasting up to 10^{2-3} s that has a GRB appearing only at its later phase; (3) an ultra-long X-ray transient lasting for $\sim 10^3$ s without a GRB. A generic feature of these transients is that their prompt emission light curves are probably periodically modulated with periods of a few to tens of seconds.

Keywords: Hydrodynamical simulations (767) — Gamma-ray bursts (629) — X-ray transient sources (1852) — White dwarf stars (1799) — Tidal disruption (1696)

1. INTRODUCTION

γ -ray bursts (GRBs) can be classified into long and short GRBs based on their T_{90} duration. It is generally believed that long GRBs ($T_{90} > 2$ s) are associated with the core collapse of massive stars and accompanied by supernova explosions, while short GRBs ($T_{90} < 2$ s) are linked to mergers of binary neutron stars (BNS) or NS-black hole (NS-BH) systems, typically accompanied by gravitational waves (GWs) and kilonovae (P. Kumar & B. Zhang 2015; B. Zhang 2018). Notably, the connection between BNS mergers and short GRBs has been observationally confirmed through GW detections (B. P. Abbott et al. 2017a,b).

Certain peculiar cases, such as GRB 230307A and 211211A, have generated substantial scientific intrigue. Their defining features include: (1) $T_{90} > 2$ s, often reaching tens of seconds (J. C. Rastinejad et al. 2022; E.

Troja et al. 2022; J. Yang et al. 2022; A. J. Levan et al. 2024; Y.-H. Yang et al. 2024; H. Sun et al. 2025); (2) consistently low redshifts (J. C. Rastinejad et al. 2022; E. Troja et al. 2022; A. J. Levan et al. 2024; Y.-H. Yang et al. 2024); (3) significant location offsets from their host galaxies (e.g., GRB 230307A shows an offset of ~ 37 kpc, A. J. Levan et al. 2024, Y.-H. Yang et al. 2024); (4) absence of late-time supernova signatures despite exhibiting kilonova-like components similar to AT 2017gfo (J. C. Rastinejad et al. 2022; Y.-H. Yang et al. 2024); (5) potential quasi-periodic modulation features in the prompt emission (J.-P. Chen et al. 2024; hereafter Paper I); (6) Other potential observational features, such as the visible dips between prompt and extended emission, the nearly constant ratio of extended to main emission energy, and an ever decreasing hardness over time (H. Sun et al. 2025; Z.-Y. Peng et al. 2024; C.-W. Wang et al. 2025; W.-J. Tan et al. 2025; B. Zhang 2025; Y.

Kang et al. 2025), point to a perplexing origin for this type of long-merger GRBs.

Generally, BNS or NS-BH mergers are unlikely to produce long GRBs lasting tens of seconds. As a potential progenitor, white dwarf (WD)-BH/NS mergers provide a new perspective for understanding the origin of long-merger GRBs (C. L. Fryer et al. 1999; A. King et al. 2007; Y.-Z. Dong et al. 2018; J. Yang et al. 2022; S.-Q. Zhong et al. 2023; N. M. Lloyd-Ronning et al. 2024; X. I. Wang et al. 2024; J.-P. Chen et al. 2024; X.-X. Liu et al. 2025; A. A. Chrimes et al. 2025). Moreover, compared with BNS or NS-BH systems, WD-BH/NS binary systems are more abundant in the universe. Therefore, their merger process merits in-depth investigation.

Using three-dimensional hydrodynamical simulations, C. L. Fryer et al. (1999) studied the merger process of a WD with a BH or NS, modeling the WD with 6,000–16,000 particles and focusing specifically on its tidal disruption process. Their findings indicate that once the stripped mass of the WD exceeds $\sim 0.2 M_\odot$, the remnant material drains into the accretion disk around the NS or BH within one orbital period, which results in a peak accretion rate of $\sim 0.05 M_\odot \text{ s}^{-1}$, suggesting that it could potentially produce long GRBs.

Since then, considerable efforts have been devoted to investigating the evolution of accretion disks formed in WD-BH/NS systems (B. D. Metzger 2012; B. Margalit & B. D. Metzger 2016; Y.-Z. Dong et al. 2018; Y. Zenati et al. 2019, 2020; M. Toscani et al. 2022; M. A. R. Kaltenborn et al. 2023; J. Morán-Fraile et al. 2024). Simulations by J. Morán-Fraile et al. (2024) demonstrate that the tidal disruption of the WD by the NS leads to the formation of an accretion disk, and that subsequent accretion onto the NS powers a strongly magnetized, mildly relativistic jet launched perpendicular to the orbital plane. Y. Zenati et al. (2019) investigated the disruption of CO-WDs by NSs, and found that the ejecta contained only a trace amount of ^{56}Ni (few $\times 10^{-3} M_\odot$), giving rise to faint, rapidly evolving, and reddened transients. Such events are substantially shorter-lived and considerably fainter than both regular and faint/peculiar Type Ia supernovae.

The candidate kilonova features found in those long-merger type GRBs were generally thought to be associated with r-process nucleosynthesis of super-heavy elements. However, M. Ristić et al. (2025) found that an ejecta with a weak r-process component, though lacking lanthanide-rich material, can also reproduce the late-time optical and near-infrared (NIR) light curves observed for GRB 211211A and 230307A (see also M. R. Mumpower et al. 2025). Furthermore, varying assumptions about the velocity distribution of a

lanthanide-lacking ejecta can also produce late-time features that mimic phenomena typically associated with heavy-element synthesis (D. Tak et al. 2023; C. L. Fryer et al. 2024).

Paper I pointed out that, due to the relatively large tidal disruption radius of a WD, a non-negligible residual orbital eccentricity e may be retained during the late stages of its merger with a NS or BH. Consequently, the WD can experience repeated tidal disruptions (RPDs) by the BH or NS. They further found quasi-periodic modulations in the prompt emission of long-merger GRBs (such as GRB 230307A, 211211A, and 060614), supporting this scenario.

In this work, we aim to numerically study in detail the RPD scenario proposed in Paper I. We use high-resolution SPH codes to simulate the late-stage evolution of WD mergers with BHs. We consider different initial WD masses and residual orbital eccentricities. Our focus encompasses the dynamical evolution of the binary system, the structural evolution of the WD, the mass transfer, and potential accretion. Note that although our simulations primarily focus on WD-BH systems, the process is also applicable to WD-NS systems, particularly for simulations in which the compact companion mass is set to $2 M_\odot$. We also explore possible observational signatures arising from the WD-BH merger, including X-ray transients and GRBs.

The paper is organized as follows. §2 briefly reviews the physical scenario. §3 describes the methodology. §4 presents the simulation results. §5 discusses the observational appearance, including the jet’s generation, power, and radiation. Conclusions are provided in §6.

2. PHYSICAL SCENARIO

A WD-BH/NS system can form in two channels, in both of which significant orbital eccentricities may appear. In the isolated stellar binary evolution channel, if the primary has an initial mass $\gtrsim 8 M_\odot$, during the late stage of stellar evolution, it eventually forms a NS or BH in a core-collapse explosion. A large-scale mass ejection from the explosion can significantly alter the binary’s orbit; even a small amount of ejected material may potentially lead to a significant increase in the orbital eccentricity.

WD-BH/NS systems can also form via dynamical capture, particularly in dense stellar environments such as globular clusters, where the resulting binaries naturally exhibit high orbital eccentricities.

For systems with initial semi-major axes of 0.01–1 AU and eccentricities of $0.5 \leq e_{\text{ini}} \leq 0.9$, the GW emission drives orbital decay circularization (P. C. Peters 1964) until the WD begins to be partially disrupted. At that

point, the eccentricity has decreased to a nearly circular range of $0 \lesssim e \lesssim 0.2$.

2.1. Start of RPD

For a binary composed of a WD with mass M_* , and a BH or NS with mass M , in an orbit of semi-major axis a and eccentricity e , the total angular momentum and total orbital energy of the binary are $J_{\text{orb}} = M_*M/(M_* + M) \times \sqrt{G(M_* + M)R_p(1 + e)}$ and $E_{\text{orb}} = -GM_*M/(2a)$, respectively, where $R_p = a(1 - e)$ is the peri-center radius.

The massradius relation of the WD is (M. Nauenberg 1972)

$$R_* = 9 \times 10^8 \left(\frac{M_*}{M_\odot} \right)^{-1/3} \left[1 - \left(\frac{M_*}{M_{\text{Ch}}} \right)^{4/3} \right]^{1/2} \text{ cm}, \quad (1)$$

where $M_{\text{Ch}} \simeq 1.44M_\odot$. At the the peri-center, the instantaneous Roche lobe radius of the WD is $R_L = 0.49 q^{2/3} R_p / [0.6 q^{2/3} + \ln(1 + q^{1/3})]$, where $q = M_*/M$ is the mass ratio (J. F. Sepinsky et al. 2007).

When $R_* > R_L$, the WD instantaneously overflows its Roche lobe, causing part of its mass to be stripped by the compact companion star. For orbits retaining some eccentricity, Roche lobe overflow occurs predominantly near R_p . Consequently, both mass transfer and subsequent accretion processes are modulated at the orbital period. This indicates that the WD undergoes RPD by the BH/NS (Paper I).

One can also define a disruption radius of the WD as (B. Paczyński 1971; M. J. Rees 1988)

$$R_t = R_* \left(\frac{M}{M_*} \right)^{1/3}, \quad (2)$$

and introduce the penetration factor $\beta = R_t/R_p$ to quantify the degree of Roche-lobe overflow. The onset condition for the Roche-lobe overflow $R_* = R_L$ corresponds to a critical penetration $\beta_0 \approx 0.5$.

The orbital period at the RPD onset is given by Kepler's third law as

$$P_0 = 50 \left(\frac{\beta_0}{0.5} \right)^{-3/2} (1 - e)^{-3/2} (1 + q)^{-1/2} \times \left(\frac{M_*}{M_\odot} \right)^{-1} \left(1 - \frac{M_*}{M_{\text{Ch}}} \right)^{0.67} \text{ s}, \quad (3)$$

where we have used the approximate form of $R_* \propto M_*^{-1/3} (1 - M_*/M_{\text{Ch}})^{0.447}$ by I. Zalamea et al. (2010) to Equation (1). Note that this period depends primarily on M_* only.

2.2. Orbital evolution during RPD

In the absence of perturbation from a third body, the orbital evolution of a WD-BH/NS binary is governed primarily by GW radiation, tidal dissipation, and mass transfer.

GW emission removes orbital energy and angular momentum, driving the two stars closer together. The corresponding time-averaged orbital shrinking and circularization rates are given by P. C. Peters (1964), and the relevant timescale is $t_{\text{GW}} \sim \text{years}$ (see Equation (5) in Paper I).

Tidal dissipation also reduces the orbital energy. Tidal forces on the surface of the WD induce non-uniform stretching and compression, thereby exciting internal non-radial oscillation modes and converting part of the orbital energy into the WD's oscillation energy (W. H. Press & S. A. Teukolsky 1977). The injected energy is approximately proportional to the square of the oscillation amplitude (J. Guillochon et al. 2011), $|\delta E_*/E_*| \approx (\delta R/R)^2$, where $E_* \approx GM_*^2/R_*$ is the gravitational binding energy of the star.

For mass transfer, under the approximation of angular momentum conservation (i.e., $\dot{J} \sim 0$ and $\dot{M}_* \sim -\dot{M}$), material flows from the WD to the BH or NS, while angular momentum is transferred back to the WD, resulting in an increase of the pericenter R_p and an expansion of the Roche lobe R_{Lobe} . If the WD expands faster than its Roche lobe, $\Delta R_* > \Delta R_L$, the mass transfer becomes unstable; otherwise, it remains stable (A. King et al. 2007; Y.-Z. Dong et al. 2018).

In a typical run of our simulations, e.g., the merger of a $1 M_\odot$ WD with a $10 M_\odot$ BH with $\beta = 0.5$, one finds that for tidal dissipation, $\delta E_*/E_* \sim 10^{-4}$, while transferring a mass of $0.1 M_\odot$ would cause $\Delta a/a \sim 0.2$. Therefore, during the RPD phase, mass transfer almost dominates entirely the orbital evolution.

3. METHODS

We use the SPH code Phantom (D. J. Price 2012; D. J. Price et al. 2018, for a detailed description of Phantom and the methodology, see D. Liptai & D. J. Price 2019). The initial WD is modeled as a polytrope with index $n = 3/2$, with its massradius relation determined by Equation (1). In all simulations, the WD is discretized into 10^6 equal-mass particles, while the NS or BH is represented by a sink particle, acting as a point mass for gravitational interactions. Throughout the simulation, both the gas in the stripped stream and the remaining WD are assumed to follow an adiabatic equation of state $\gamma = 5/3$ (D. Garain & T. Sarkar 2025). Note that the true equation of state of a WD is much more complex,

Table 1. Simulation Initial Parameters and Results

Sim. ID	Initial Parameters							Sim. Results			
	M_*	M	q	β_0	e_0	a_0	P_0	$\dot{M}_{peak}$	$\dot{M}_{mean}$	RPD Duration	Category
	($M_\odot$)	($M_\odot$)				($R_\odot$)	(s)	($M_\odot/s$)	($M_\odot/s$)	(s)	
No. 1a	0.8	10	0.08	0.45	0.2	6.6E-2	51.9	8.1E-4	2.1E-4	1190 ($\sim 21 P$)	III
No. 2a	1	10	0.1	0.45	0.2	4.8E-2	31.2	3.4E-3	6.3E-4	615 ($\sim 18 P$)	
No. 4	1	10	0.1	0.4	0.2	5.4E-2	37.9	3.8E-4	8.9E-5	2800 ($\sim 65 P$)	
No. 6a	1	10	0.1	0.45	0.05	4.0E-2	24.6	1.27E-3	5.0E-4	825 ($\sim 26 P$)	
No. 7a	1	10	0.1	0.45	0.1	4.3E-2	26.6	1.36E-3	3.9E-4	1040 ($\sim 31 P$)	II
No. 8a	0.8	2	0.4	0.45	0.2	3.9E-2	45.6	3.9E-3	1.1E-3	420 ($\sim 9 P$)	
No. 0a	1	10	0.1	0.45	0.01	3.8E-2	22.7	2.2E-3	1.2E-3	220 ($\sim 9 P$)	
No. 2	1	10	0.1	0.5	0.2	4.3E-2	27.1	6.0E-3	1.6E-3	99 ($\sim 3 P$)	
No. 3a	1.3	10	0.13	0.45	0.2	2.3E-2	10.5	6.5E-3	2.0E-3	270 ($\sim 23 P$)	
No. 5	1	10	0.1	0.6	0.2	3.6E-2	20.6	7.5E-3	3.6E-3	38 ($\sim 2 P$)	
No. 6	1	10	0.1	0.5	0.05	3.6E-2	21.0	1.2E-2	4.9E-3	43 ($\sim 2 P$)	
No. 7	1	10	0.1	0.5	0.1	3.8E-2	22.7	9.0E-3	2.5E-3	62 ($\sim 3 P$)	
No. 10a	1.3	2	0.65	0.45	0.2	1.4E-2	8.7	8.5E-2	2.2E-2	27 ($\sim 3 P$)	I
No. 9	1	2	0.5	0.5	0.2	2.5E-2	23.2	2.4E-2	1.0E-2	43 ($\sim 2 P$)	
No. 10	1.3	2	0.65	0.5	0.2	1.2E-2	7.4	0.13	4.8E-2	12.2 ($\sim 1 P$)	
No. 11	1.4	5	0.28	0.5	0.2	8.5E-3	3.1	0.16	5.3E-2	7.5 ($\sim 2 P$)	

NOTE— M_* , M , and q represent the WD mass, the BH/NS mass, and the mass ratio ($q = M_*/M$). β_0 , a_0 , e_0 , and P_0 denote the initial penetration factor, orbital eccentricity, orbital semi-major axis, and orbital period. $\dot{M}_{peak}$, $\dot{M}_{mean}$, and RPD duration correspond to the peak accretion rate, mean RPD accretion rate, and the simulation RPD duration (in units of s). The last column lists the category, in which all simulations are classified into three categories based on the $\dot{M}_{mean}$ of 10^{-3} and $10^{-2} M_\odot s^{-1}$.

and the adopted one is an approximation that may deviate from the reality.

The WD is placed on an elliptical orbit, initially near the aphelion R_a , with a velocity $v_0 = \sqrt{2GM/R_a}$, and its orbital motion is counterclockwise in the x - y plane. Since the WD remains at relatively large distances from the BH during mass transfer ($R_p \geq 100 R_s$), general relativistic effects are neglected. To avoid extremely small time steps near the BH event horizon, particles that fall into a fixed accretion radius (set to $R_{acc} = R_p/3$, see §4.3) are immediately removed.

3.1. Initial parameters

WD-NS or WD-BH binaries gradually lose orbital energy and angular momentum through the GW emission over the timescale t_{GW} . In our simulations, we adopt two approximate values of β_0 , 0.45 and 0.5, as the initial conditions. We also had two additional runs with $\beta_0 = 0.4$ and 0.6, respectively, to investigate our results' dependence on β_0 (see §4.4).

All simulations focus exclusively on massive WDs, with their initial masses set to $M_* = 0.8, 1.0$, and $1.3 M_\odot$, respectively. The BH mass is fixed at $M = 10 M_\odot$ and $5 M_\odot$, respectively, while NSs are approximated as point masses of $M = 2 M_\odot$. Initial orbital eccentricities of $e_0 = 0.05, 0.1$, and 0.2 , respectively, are adopted based on the estimate in §2. For demonstrating the role

of eccentricity (see §4.4), we had an additional run with $e_0 = 0.01$.

Table 1 lists all 16 simulation runs, along with their initial parameters and simulation results.

4. RESULT

We start with the run of the merger of a $1 M_\odot$ WD and a $10 M_\odot$ BH as a representative case, presenting the simulation results on the structure of the WD (§4.1) and the orbital evolution (§4.2). §4.3 and 4.4 respectively present the mass accretion processes from several simulations and analyze the parameter dependence of the results within the simulation ensemble.

4.1. WD structure

The binary system in the simulation run No. 2a (with $\beta_0 = 0.45$, $e_0 = 0.2$, $P_0 = 31.2$ s, see Table 1), exhibits distinct evolutionary phases during its first orbital period as captured by time-equidistant snapshots on the x - y plane shown in Figure 1. At simulation onset ($t = 0$ s), the WD occupies R_a , its trajectory marked by the white dashed line. Incipient tidal deformation emerges at $t = 10.0$ s, preceding a morphological transition at R_p passage ($t = 20.6$ s) where the WD evolves from spherical to an ellipsoidal shape with pronounced teardrop distortion, simultaneously developing a substantial debris stream directed toward the BH.

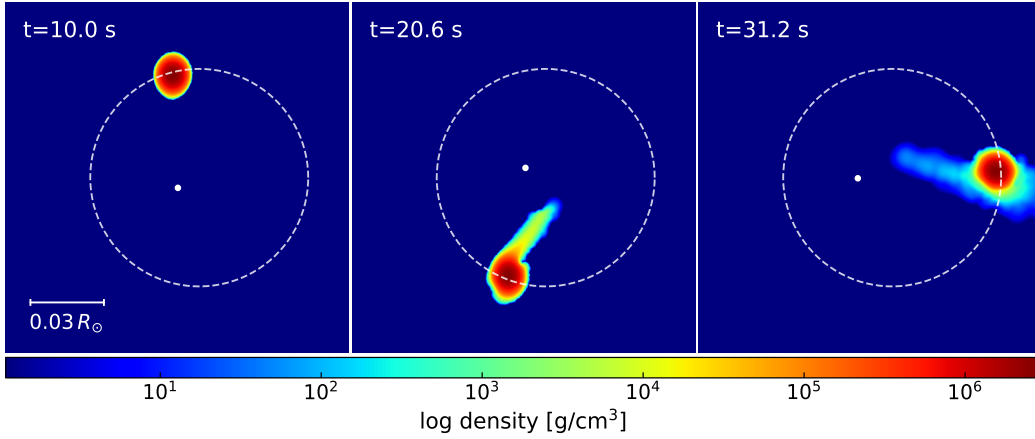


Figure 1. Density evolution of the WD over one orbital period. We present density projection snapshots in the xy plane from a simulation using 10^6 SPH particles to model the late merger phase of a $1 M_\odot$ WD interacting with a $10 M_\odot$ BH (for simulation runs No. 2a). Each panel covers a region of $0.14 \times 0.14 R_\odot$.

Subsequent evolution at $t = 31.2$ s (right panel of Figure 1) reveals structural reconvergence toward sphericity for the WD at R_a , while stripped material bifurcates: one component accelerates toward the BH for accretion, whereas the remaining debris is gravitationally pulled to the WD.

Determining the exact amount of residual material that remains bound to the WD after experiencing a partial disruption is a highly challenging task. As an alternative approach, C. Liu et al. (2025) defined a threshold surface density (ρ_t) established after relaxation, where all the material with $\rho > \rho_t$ is considered bound to the star. Adopting this approach, we determine the residual structure of the WD after each stripping and hence the new M_* and R_* .

4.2. Orbital evolution

Figure 2 presents a series of density snapshots in the xy plane at representative orbital phases during the No. 2a run. Two distinct debris streams are observed to extend from the two sides of the WD, with the stream directed toward the BH being gravitationally captured by the latter. Over successive orbits, spiral arms develop and exhibit progressive density enhancement on both flanks of the WD, thereby intensifying the partial disruption process. This evolutionary pattern is consistent with the scenario predicted in Paper I.

Panels (a)-(e) of Figure 3 show the evolution of M_* , R_* , R_p , a , and β during the RPDs ($t = 0 - 620$ s, for the No. 2a run). As the WD undergoes RPDs, its mass M_* gradually decreases, while the WD expands and its radius R_* increases. The orbital parameters, R_p and a , also grow with time, but β exhibits an overall increasing trend. This behavior implies that the RPDs proceed

through an unstable mass-transfer process, ultimately leading to the complete disruption of the WD.

At $t \approx 620$ s (at R_a), the WD undergoes complete structural disruption, which we define as the end of the RPDs. The main panel of Figure 2 shows the density distribution at $t = 691.8$ s, when the WD structure has almost entirely disappeared and the remaining debris is streaming toward the BH. A disk-like structure forms around the BH, and matter is continuously accreted into the accretion radius indicated by the black dashed circle in Figure 2.

4.3. Mass Accretion History

The exact and detailed evolution of the accretion disk involves processes such as viscosity, radial drift of the disk material, and potentially neutrino cooling and nuclear burning (B. D. Metzger 2012; R. Fernández & B. D. Metzger 2013; B. Margalit & B. D. Metzger 2016) and is beyond the scope of this study. To simplify the accretion rate estimation, we adopt a relatively large accretion radius, $R_{acc} \sim R_p/3$, and consider every particle that falls into R_{acc} as being immediately accreted.

Figure 4 shows the evolution of the accretion rate $\dot{M}$ for simulations No. 1a, 8a, and 10a, respectively. In simulation No. 1a (initial parameters $M_* = 0.8 M_\odot$, $M = 10 M_\odot$, $\beta_0 = 0.45$, and $e_0 = 0.2$), throughout the RPD phase, the accretion rate displays strong fluctuations on the orbital timescale. The peak accretion rate $\dot{M}_{peak}$ reaches $\sim 8.1 \times 10^{-4} M_\odot \text{ s}^{-1}$ at $t \sim 1150$ s, when the WD structure is nearly destroyed. The RPD phase extends to about $t \sim 1200$ s ($\sim 21 P$, indicated by the red vertical dashed line in Figure 4), after which the remnant material is accreted over a few orbital periods, with the $\dot{M}_{peak}$ gradually decreasing.

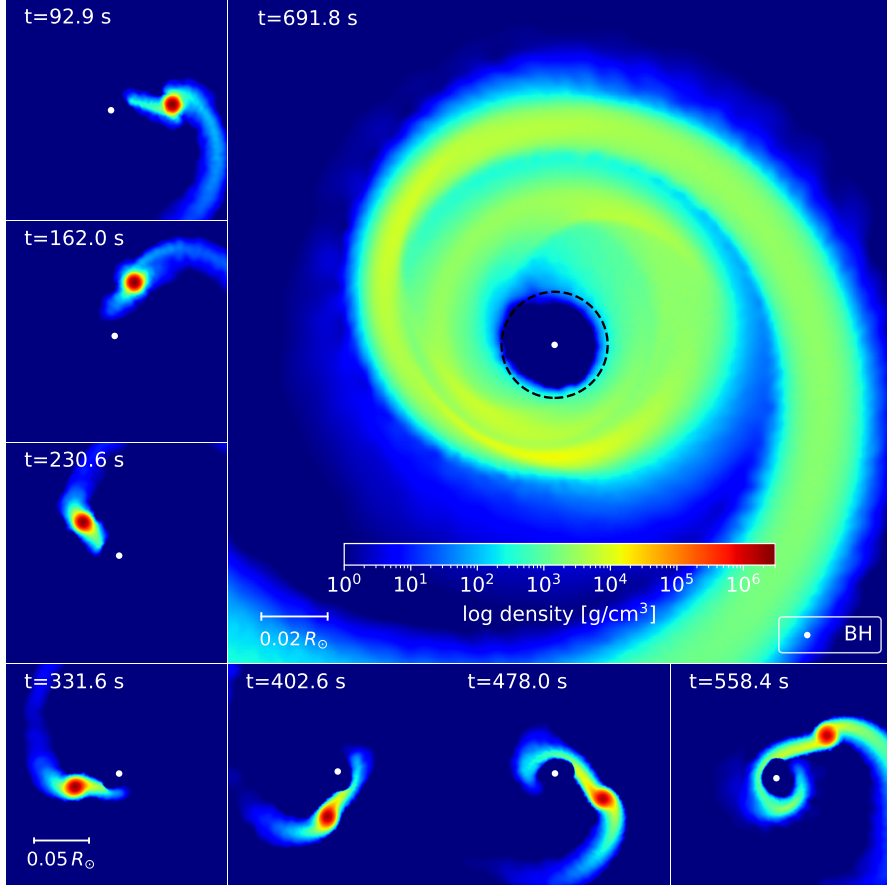


Figure 2. Repeating Partial Disruption Process of a WD. We present densityprojection snapshots in the x - y plane from a simulation using 10^6 SPH particles to model the late merger phase of a $1 M_\odot$ WD interacting with a $10 M_\odot$ BH (for simulation runs No. 2a). Each panel corresponds to distinct evolutionary times, with all panels spanning a physical scale of $0.2 \times 0.2 R_\odot$. The main panel shows the WD after complete disruption (the end of the RPD is defined as $t = 620$ s), where the black dashed circle marks the accretion radius $R_{\text{acc}} = R_p/3$. A video showing the density evolution of this simulation can be found at https://youtube.com/shorts/o1G_qp9Fnpg?feature=share.

For simulation No. 8a (initial $M_* = 0.8 M_\odot$, $M = 2 M_\odot$), compared with simulation No.1a, the larger q leads to a markedly shorter RPD phase. At $t \sim 400$ s, the peak accretion rate reaches its $\dot{M}_{\text{peak}} \simeq 3.9 \times 10^{-3} M_\odot \text{ s}^{-1}$. By $t \sim 420$ s ($\sim 9 P$), the WD structure is nearly destroyed, marking the end of the RPD phase, followed by the subsequent accretion of the remaining debris material.

For simulation No. 10a (initial $M_* = 1.3 M_\odot$, $M = 2 M_\odot$), the nearly-equal component masses and, most importantly, the much more compact WD lead to a much shorter orbital period compared with No. 1a and No. 8a. It has $\dot{M}_{\text{peak}} \simeq 8.5 \times 10^2 M_\odot \text{ s}^{-1}$ at $t \sim 27$ s, and the RPD phase is highly violent, lasting for about 30 s ($\sim 3 P$).

We find that for all our simulations, the accretion history is strongly modulated by the orbital period, as is shown by the representative cases in Figure 4.

The initial eccentricity e_0 plays a crucial role in modulating the accretion rate, as is shown in Figure 5. We define the modulation amplitude as $A = \dot{M}_{\text{max}}/\dot{M}_{\text{min}}$, where $\dot{M}_{\text{max}}$ is the peak accretion rate and $\dot{M}_{\text{min}}$ is the minimum accretion rate within the same orbital cycle that contains the peak. Larger values of A indicate stronger modulation. Figure 5 depicts a clearly positive relation between e_0 and A obtained from our simulations.

However, the viscous evolution of the disk, not included in the simulations, may act to smooth out this modulation. The viscous timescale of the disk can be estimated as $t_{\text{vis}} = R_p^2/\nu \simeq (P/2\pi\alpha)(H/R)^{-2}$, where α is the ShakuraSunyaev viscosity parameter and H/R is the disk aspect ratio. During the RPD phase, the accretion rate is extremely high, $\dot{M} \gg \dot{M}_{\text{Edd}}$, so $H/R \simeq 1$, the disk is geometrically thick. Then for $\alpha \sim 0.1$, one would have $t_{\text{vis}} \approx P$. Therefore, we expect that the

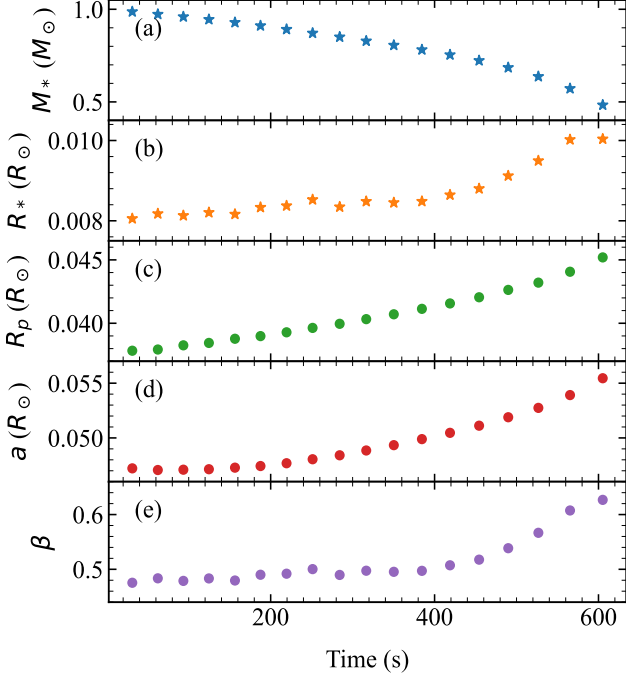


Figure 3. Late-stage parameter evolution of a $1 M_\odot$ WD merging with a $10 M_\odot$ BH (for simulation runs No. 2a). Panels (a), (b), (c), (d), and (e) show the evolution of WD's mass M_* , radius R_* , pericenter distance R_p , semi-major axis a , and penetration factor β , respectively.

orbital modulation of the accretion rate may still leave imprints on the light curve.

4.4. Classification and parameter dependence

Table 1 summarizes the peak ($\dot{M}_{peak}$) and mean ($\dot{M}_{mean}$) accretion rates, and RPD durations for all simulations. It shows a range of $10^{-4} \lesssim \dot{M}_{mean} \lesssim 10^{-1} M_\odot \text{ s}^{-1}$, and the RPD durations vary from 10 s to a few $\times 10^3$ s.

In the decreasing order of their values of $\dot{M}_{mean}$, we classify all the simulation runs into three categories:

- **Category I:** represented by run No. 10a (see Figure 4), including No. 9, 10, and 11, whose $\dot{M}_{mean}$ is $\gtrsim 10^{-2} M_\odot \text{ s}^{-1}$, with the RPD duration $\lesssim 10^2$ s.
- **Category II:** represented by run No. 8a, including No. 0a, 2, 3a, 5, 6, and 7, whose $\dot{M}_{mean}$ is intermediate: $10^{-3} \lesssim \dot{M}_{mean} \lesssim 10^{-2} M_\odot \text{ s}^{-1}$. The RPD phase typically lasts for 10^2 - 10^3 s.
- **Category III:** represented by run No. 1a, including No. 2a, 4, 6a, and 7a. They are characterized by relatively low accretion rates, $\dot{M}_{mean} \lesssim 10^{-3} M_\odot \text{ s}^{-1}$. The RPD phase can last more than 10^3 s.

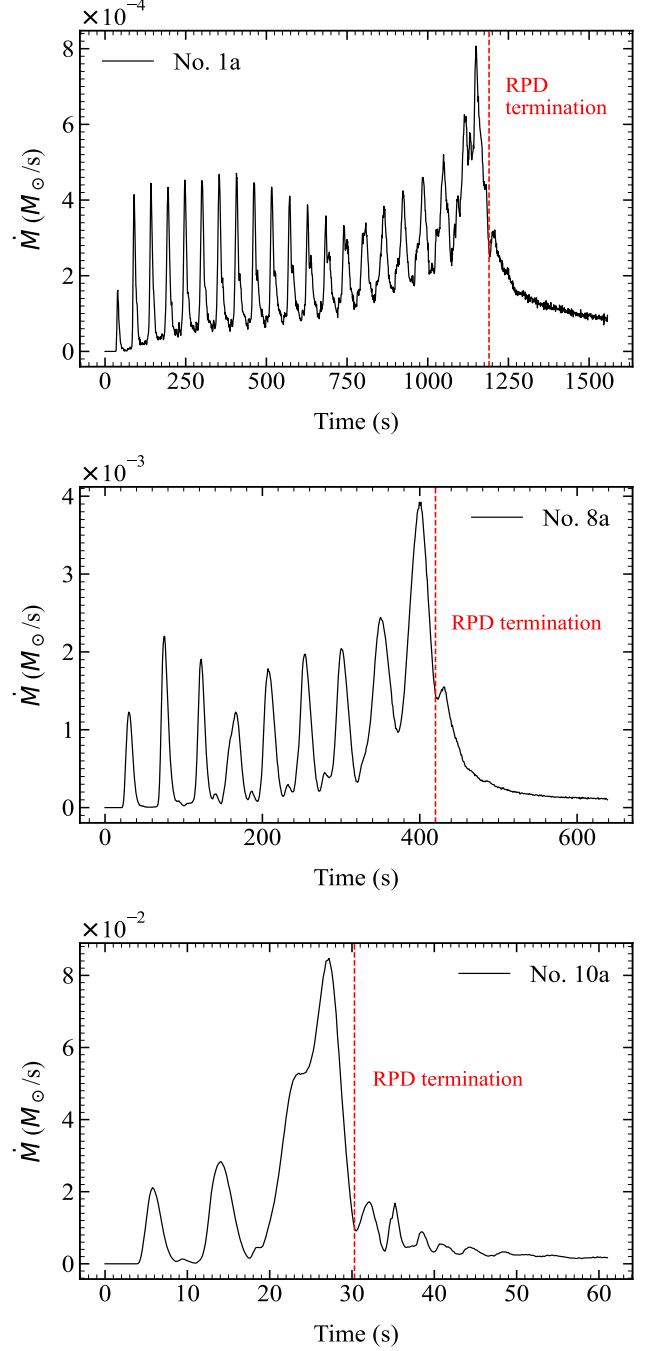


Figure 4. Evolution of the accretion rate during the late stage of the WDBH merger for simulation runs No. 1a, 8a, and 10a. The red vertical dashed line indicates the termination of the repeated partial disruptions of the WD. Each panel corresponds to one of the three categories described in §4.4.

Compared with Categories II and III, Category I shows a larger modulation amplitude A , but with fewer RPD cycles.

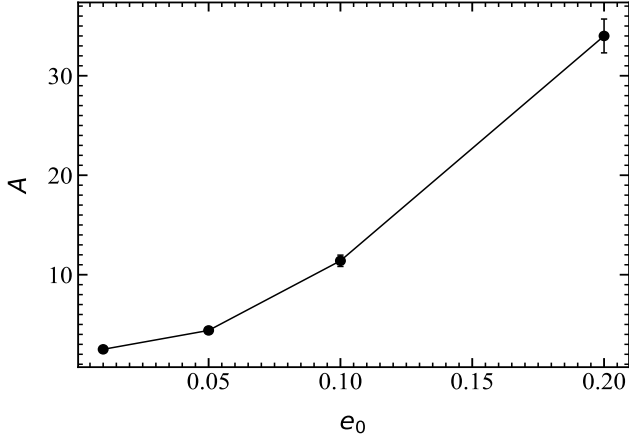


Figure 5. The relationship between the initial orbital eccentricity e_0 and the modulation amplitude $A = \dot{M}_{max}/\dot{M}_{min}$ obtained from simulation runs No. 0a, 2a, 6a, and 7a. The error bars represent the statistical standard errors of our measurements.

To delineate the factors behind the outcome variations among these categories, we plot in Figure 6 the relation of $\dot{M}_{mean}$, the RPD duration, and the number of RPD cycles versus the initial orbital size a . The main conclusions are: (1) $\dot{M}_{mean}$ decreases with increasing a ; and (2) both the RPD duration and the number of cycles increase with increasing a . We also find similar trends of these three quantities of simulation outcomes with decreasing q or increasing P_0 , but they are somewhat weaker than those shown in Figure 6.

Figure 7 plots the successive evolution of the remnant WD’s radius and mass throughout the RPD process for simulations No. 10a, 8a, and 2a, corresponding to Categories I, II, and III, respectively. During the RPDs, as is shown in Figure 7, the WD radius expansion rate $|dR_*/dM_*|$, which signifies the degree of unstableness of the mass transfer, somehow follows the sequence of Category I > II > III. This order explains why more compact systems – with smaller a or higher mass ratio q – exhibit fewer cycles, thus shorter durations and higher accretion rates.

We also plot in Figure 8 the relation of the number of RPD cycles versus the initial penetration factor β_0 , from simulation runs No. 2, 2a, 4, and 5. It is evident that the number of RPD cycles decreases with increasing β_0 , indicating that the RPD process becomes more violent for deeper encounters.

5. OBSERVATIONAL APPEARANCE

Based on our simulation results, below we discuss the observational consequences of a jetted WD-BH/NS merger.

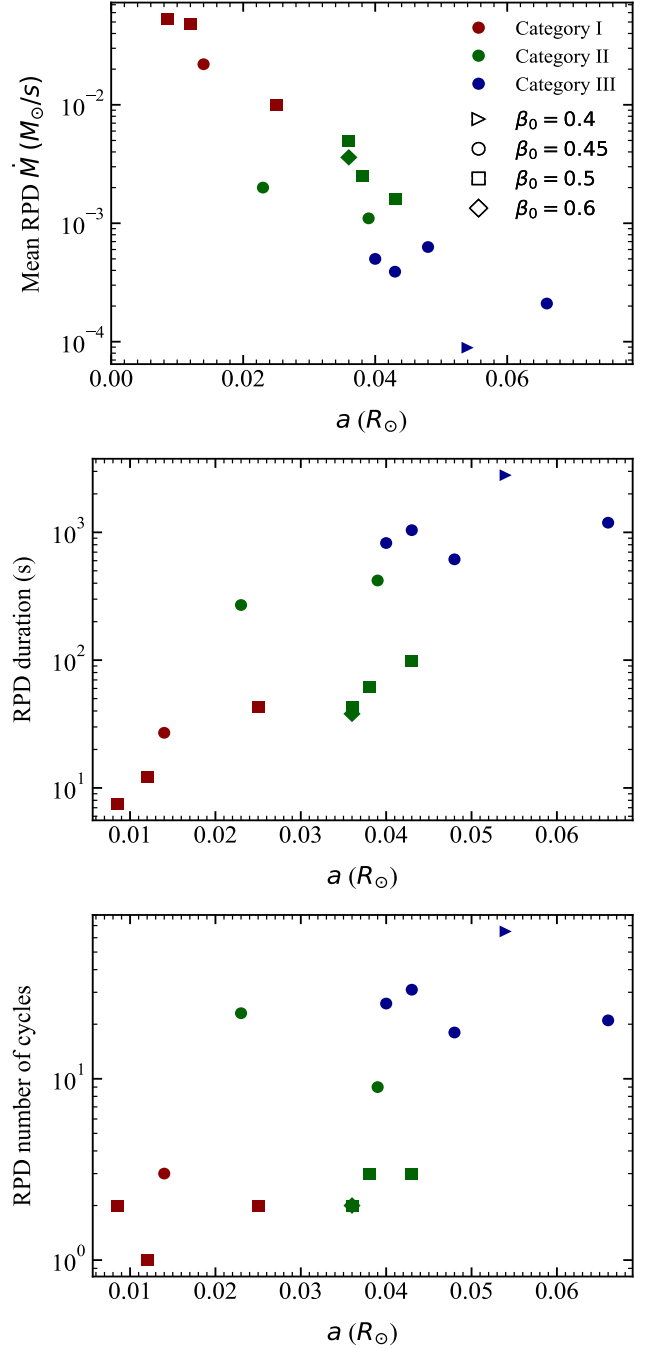


Figure 6. The relations of $\dot{M}_{mean}$, the RPD duration, and the number of RPD cycles versus the initial orbital semi-major axis a , among all our simulation runs. Dark red, dark green, and dark blue represent Categories I, II, and III, respectively. Triangles, circles, squares, and diamonds correspond to $\beta_0 = 0.4, 0.45, 0.5$, and 0.6 , respectively.

5.1. Generation of Jets

In the RPD scenario of a WD-BH/NS merger, the central engine is an accreting BH or accreting NS. A

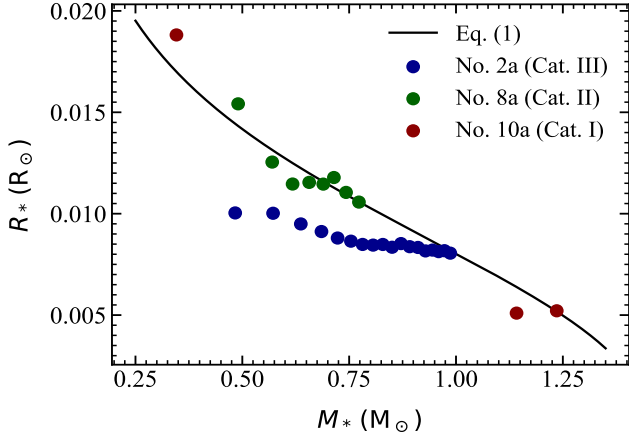


Figure 7. The successive evolution of the remnant WD mass M_* and radius R_* during the RPD process is shown for three representative simulation runs: No. 10a (Category I), 8a (Category II), and 2a (Category III). Their initial M_* values are 1.3, 0.8, and $1.0 M_\odot$, respectively. Following each partial disruption, the WD loses mass and undergoes expansion. The black line represents Equation (1), i.e., the mass-radius relation of an isolated, cold WD.

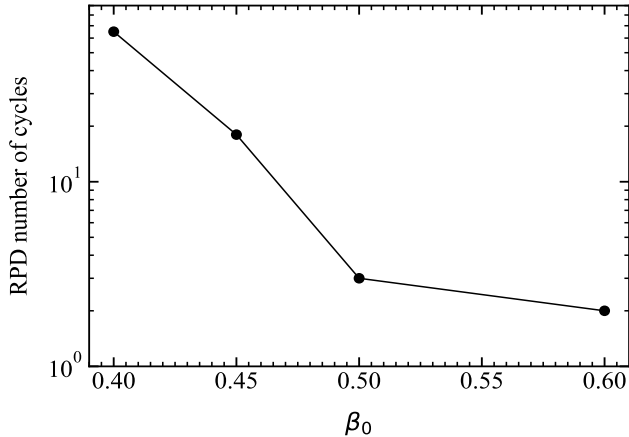


Figure 8. The relationship between the initial penetration factor β_0 and the number of RPD cycles obtained from simulation runs No. 2, 2a, 4, and 5 whose initial parameters are the same except for β_0 .

jet could be launched, the mechanism of which is either neutrino-driven or magnetically driven, or both.

When the central engine is a BH, in the disk innermost region close to the BH, where the temperature is extremely high, electrons and positrons are captured, leading to copious neutrino production within the disk. Neutrinos (ν) and antineutrinos ($\bar{\nu}$) can annihilate to produce photons and electron-positron pairs, while neutrinos may also strip baryons off the disk (Y. Z. Qian & S. E. Woosley 1996; R. Popham et al. 1999; C. L. Fryer et al. 1999; T. Liu et al. 2017). A hot “fireball” with

modest baryon contamination is then formed above the accretion disk. Because the energy deposition region is located near the disk symmetry axis, where baryon loading is relatively low, the fireball can be efficiently accelerated into a relativistic jet. The disk outflow or wind may further collimate the jet.

The accretion process can also increase the BH’s spin. A higher spin corresponds to a higher temperature in the innermost region of the disk. The luminosity of a neutrino-cooling driven jet is estimated as $\log L_{\nu\bar{\nu}} \simeq 44 + 5 \log(\dot{M}_{-2}) + 3.4 a_*$ [erg s $^{-1}$] (R. Popham et al. 1999; C. L. Fryer et al. 1999), where $\dot{M}_{-2} = \dot{M}/0.01 M_\odot \text{ s}^{-1}$ and $a_* = J_{\text{BH}} c/GM^2$, with J_{BH} being the angular momentum of the BH.

If the accretion disk is highly magnetized and the rapidly spinning BH is threaded by magnetic field lines that connect the event horizon to distant plasma, the BH’s rotational energy can be extracted via the Blandford-Znajek (BZ) mechanism (R. D. Blandford & R. L. Znajek 1977). This process drives a Poynting-flux-dominated jet, which can be self-collimated by the strong toroidal magnetic field generated by the rapidly rotating central engine (H. K. Lee et al. 2000; M. H. P. M. van Putten 2001), with an estimated luminosity of $L_{\text{BZ}} = 10^{50} a_*^2 (M/3M_\odot)^2 (B/10^{15} \text{ G})^2 \text{ erg s}^{-1}$ (R. D. Blandford & R. L. Znajek 1977).

When the central engine is a NS, the stripped WD material may also form a neutrino-cooled accretion disk. Unlike a BH, a NS possesses a solid surface, which renders the innermost disk region denser and hotter. Consequently, the neutrino luminosity is significantly higher than that of a BH disk (D. Zhang & Z. G. Dai 2008, 2009, 2010).

In addition, for an accreting NS, the rigid-body rotational frequency of the core exceeds that of the outer envelope, giving rise to differential rotation (W. Kluźniak & M. Ruderman 1998; M. A. Ruderman et al. 2000; Z. G. Dai et al. 2006). As a consequence, the toroidal magnetic field is amplified and a magnetically confined toroidal structure is formed within the NS. When the magnetic field grows sufficiently strong, a magnetic bubble eruption can take place, which in turn drives a jet, with a luminosity of $L_{\text{jet}} = \eta \dot{M} c^2 \simeq 1.8 \times 10^{51} \eta_{-1} \dot{M}_{-2} \text{ erg s}^{-1}$, where $\eta = 10\% \times \eta_{-1}$ denotes the efficiency of converting accretion power into jet power (W. Kluźniak & M. Ruderman 1998; M. A. Ruderman et al. 2000; B. B. Zhang et al. 2021; J. Yang et al. 2022; S.-Q. Zhong et al. 2023). For rapidly rotating NSs, rotational energy can also be extracted through magnetic dipole radiation, contributing to powering the jet (S. L. Shapiro & S. A. Teukolsky 1983; V. V. Usov 1992; B. Zhang & P. Mészáros 2001).

Particularly, in scenarios involving a high-mass NS, as the mass of the NS grows up to a limit $\sim 3 M_\odot$ during the RPD process, it would collapse into a BH, a phenomenon known as the accretion-induced collapse (AIC, B. Qin et al. 1998; C. D. Dermer & A. Atoyan 2006; R. Perna et al. 2021). An intriguing electromagnetic signature may be associated with this collapse. During the AIC, the formation of an event horizon conceals most of the matter and radiation, with the exception of the NS magnetosphere: it undergoes violent disruption, leading to magnetic reconnection and the release of high-energy electromagnetic radiation. The exact characteristic of this radiation is still under debate, but it has been proposed as a potential explanation to both long or short GRBs (M. Vietri & L. Stella 1999; C. D. Dermer & A. Atoyan 2006), as well as fast radio bursts (H. Falcke & L. Rezzolla 2014).

5.2. Jet radiation

As the jet accelerates and propagates, part of its thermal energy or Poynting flux is converted into the kinetic energy, allowing the jet to reach relativistic speeds. A fraction of the initial thermal energy is radiated as photons from the jet photosphere, while the remaining kinetic energy or Poynting flux is dissipated within the jet to accreting charged particles via mechanisms such as shock acceleration, magnetic reconnection, and turbulence (B. Zhang 2018). The accelerated particles subsequently produce non-thermal radiation through synchrotron emission and inverse Compton scattering, primarily in the X-ray to γ -ray bands.

The spectral peak of the jet radiation strongly depends on the jet power and Lorentz factor Γ_{jet} , which in turn depend on the energy power and extraction efficiency of the central engine (C. L. Fryer et al. 1999). Jets from lower-power systems have smaller Γ_{jet} , and electrons in the comoving frame reach only mildly relativistic values γ_e , resulting in emission mainly in the soft to hard X-ray bands. In contrast, systems with higher central engine power, which we relate to higher $\dot{M}_{mean}$, would produce jet radiation with the spectral peak reaching the γ -ray bands.

5.3. X-ray transients and γ -ray bursts

Below, we predict a variety of non-thermal transients from a jetted WD-BH/NS merger system that corresponds to Categories I, II, and III, respectively, of our simulation runs. They are: (i) X-ray transients with simultaneous GRBs; (ii) Long-duration X-ray transients accompanied by GRBs only at late times; (iii) Ultra-long X-ray transients.

It is important to note that the accretion rates derived from our simulations are not anticipated to directly mir-

ror the realistic behavior of light curves. Since radiative emission is contingent upon numerous factors, including radiative transfer, jet generation, and viscous processes (see discussion in §4.3), we do not model the realistic light curve and spectral evolution in this context. Instead, we just give some qualitative predictions on the possible observational signatures.

- X-ray transients with simultaneous GRBs

Category I generally corresponds to systems involving a more massive WD (e.g., $M_* \simeq 1.1\text{--}1.3 M_\odot$) and a less massive (e.g., $\lesssim 5 M_\odot$) BH or NS, resulting in an extremely violent RPD process and a very high accretion rate. We expect that Category I systems may produce both X-ray transients and GRBs simultaneously, with the duration of their prompt emission lasting up to $\sim 10^2$ s.

Moreover, although the accretion rate in Category I shows large modulation amplitudes, the number of RPD cycles is relatively small. Consequently, the observed X-ray and γ -ray light curves may exhibit only a limited number of modulation periods, albeit with pronounced amplitudes.

- Long-duration X-ray transients accompanied by GRBs only at late times

The accretion history of Category II systems during the RPD process generally exhibits an increasing trend of $\dot{M}_{peak}(t)$, reaching its maximum near the end of the RPD stage. Therefore, we expect that Category II systems may give rise to X-ray transients with durations of $10^2\text{--}3$ s, which could have a GRB appearing in the late phase of the X-ray transient.

In addition, the number of accretion rate modulations in Category II events is larger than that in Category I, implying that the X-ray and γ -ray light curves of Category II events may contain more modulation cycles, which makes them easier to identify observationally. Moreover, the overall modulation amplitude is also relatively large.

- Ultra-long X-ray transients

Compared with Categories I and II, Category III generally corresponds to systems involving a less massive WD (e.g., $M_* \lesssim 1 M_\odot$) and a more massive BH (e.g., $M_* \gtrsim 10 M_\odot$). During the early stage of the RPD process, the accretion rate is relatively low and the jet is weak. As the accretion rate increases, the jet becomes stronger and then may produce an X-ray transient with a duration of up to 10^3 s. It might lack a GRB because the jet is not sufficiently strong.

The X-ray transient light curve would exhibit a larger number of modulation cycles, making it easier to identify observationally. However, in systems with lower orbital eccentricities, the modulation amplitude might be weak.

In summary, we expect that during the RPD phase, Categories I, II, and III may give rise to X-ray transients with different durations, with Categories I and II possibly accompanied by GRBs. In addition to the prompt emission, the subsequent deceleration of the jet or outflows is expected to give rise to afterglow emissions. Both the prompt and early afterglow emissions of these X-ray transients are good prospect sources for wide-field X-ray instruments, such as the Einstein Probe (EP, W. Yuan et al. 2015).

5.4. Observational Cases

GRBs 230307A and 211211A can be classified as Category I events in our WD-BH/NS scenario, based on their γ -ray emission properties. From the modulation periods of their prompt emission, the corresponding WD masses are inferred to be 1.3 and 1.4 $M_\odot$ (Paper I). These values are also consistent with the expected characteristics of Category I systems. We expect Category I events to exhibit nearly simultaneous GRB and X-ray emission; however, unfortunately, no instrument captured the early X-ray transient for either of these two events.

Another noteworthy feature of GRBs 230307A and 211211A is the presence of extended emission following the prompt phase. In Figure 4, the red dashed line marks the end of the RPD phase, corresponding to the time when the WD structure becomes almost completely destroyed in the simulation. As the main panel of Figure 2 shows, at this point a final relic is left, whose accretion rate into the BH evolves slowly, and the modulation feature nearly disappears. All of these are consistent with the observed characteristics of the extended emission from GRBs 230307A and 211211A.

Faint, rapidly evolving, and reddened transients powered by the radioactive decay of ^{56}Ni in the ejecta of WD-BH/NS systems provide a plausible origin for the late-time kilonova-like optical/NIR transients observed in GRBs 230307A and 211211A (B. D. Metzger 2012; Y. Zenati et al. 2020).

EP150702a / GRB 250702B is a remarkable transient that showed a ~ 0.73 -day (rest-frame) rise in soft X-rays, during which MeV emission was observed about three hours prior to the soft X-ray peak, resulting in at least three Fermi-GBM triggers (A. J. Levan et al. 2025; G. Oganessian et al. 2025; D. Y. Li et al. 2025).

Its prompt emission light curves in both MeV and soft X-ray bands show several distinct flares. This behavior is consistent with the RPD scenario of a WD-BH/NS

merger and the prediction from our simulations. Moreover, the spectral evolution from soft X-ray to MeV energies, concurrent with the pre-peak rapid rise of the X-ray flux (D. Y. Li et al. 2025), may indicate a progressively intensifying process, which is consistent with the ever-increasing trend of $\dot{M}_{\text{peak}}(t)$ during the RPDs seen in our simulations.

The fact that its MeV emission appeared only near the X-ray peak suggests a Category II classification in our WD-BH/NS scenario. However, the ultra-long duration ($\sim 6 \times 10^4$ s) of the X-ray transient before the peak resembles the characteristic of Category III. Compared with the other two categories, producing a GRB in a Category III system is more challenging, although it remains possible when magnetic effects are taken into account. We note that a (or repeated) tidal disruption event of a WD by an intermediate-mass BH has been proposed to explain this transient (A. J. Levan et al. 2025; D. Y. Li et al. 2025; R. A. Eyles-Ferris et al. 2025). Overall, a WD-BH/NS system as the progenitor of EP250702a / GRB 250702B cannot be ruled out.

6. CONCLUSIONS

Recent studies suggest that mergers of WDs with NSs or stellar-mass BHs may be potential progenitors of unusually long GRBs, such as GRBs 230307A and 211211A. Compared to NS-NS or NS-BH mergers, the larger tidal disruption radius of a WD can result in a non-negligible residual orbital eccentricity during the late merger stage ($0 < e \leq 0.2$). This residual eccentricity can lead to discontinuous mass transfer, with the WD undergoing RPDs.

Using SPH simulations with 10^6 particles, we modeled the late-stage mass transfer processes in WD-NS and WD-BH mergers, tracking the evolution of the accretion rate until accretion effectively ceased. Our main conclusions are as follows:

1. We reproduce the process of a WD undergoing RPDs by a NS or BH. On an orbit with a small residual eccentricity, the WD experiences RPDs near R_p , which modulate the subsequent accretion process and cause the accretion rate to vary periodically with the orbital period.
2. Simulations indicate that more compact configurations—with higher initial WD mass and lower BH mass, smaller semi-major axis a , or shorter orbital period—exhibit higher expansion rates of the WD remnant ($|dR_*/dM_*|$) and higher $\dot{M}_{\text{mean}}$. As a result, the RPD duration is shorter, and the number of cycles is reduced.

3. In decreasing order of $\dot{M}_{mean}$, all simulation results can be classified into three categories.

- Category I: Their $\dot{M}_{mean}$ exceeds $10^{-2} M_{\odot} \text{ s}^{-1}$, and the RPD phase can last up to 10^2 s. Such RPD episodes occur less frequently but exhibit larger modulation amplitudes. They are likely to produce X-ray transients and GRBs almost simultaneously, with the prompt emission lasting up to 10^2 s.
- Category II: Their $\dot{M}_{mean}$ lies in the range of 10^{-3} – $10^{-2} M_{\odot} \text{ s}^{-1}$. The RPD phase typically lasts for 10^{2-3} s. These systems may give rise to long-duration X-ray transients lasting up to 10^{2-3} s, with GRB emission appearing only at later times.
- Category III: Their $\dot{M}_{mean}$ is below $10^{-3} M_{\odot} \text{ s}^{-1}$. The duration of the RPD phase can reach 10^3 s. Such systems may generate an ultra-long X-ray transient only (although the possibility of an accompanying

GRB cannot be ruled out, it is less likely), with durations up to 10^3 s.

4. We anticipate that a common feature of these high-energy transients would be that their prompt emission—as opposed to their possible afterglow emissions—light curves are probably modulated to varying degrees by the orbital period.
5. Our simulations further indicate that the prompt emissions of GRBs 230307A and 211211A originate from the RPDs in WD-BH/NS systems, while their extended emissions may be attributed to the accretion of the final debris after the WD’s complete disruption. The recently detected EP250702a/ GRB 250702B may also arise from this scenario.

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