GRBs from Collapse of Thorne–Żytkow–like Objects as the Aftermath of WD-NS Coalescence

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Abstract

The Type II gamma-ray burst (GRB) 200826A challenges collapsar models by questioning how they can generate a genuinely short-duration event. The other Type I GRB 211211A confused us with a kilonova signature observed in the afterglow of a long burst. Here, we propose a comprehensive model in which both bursts are the results of the collapse of Thorne–Żytkow–like objects (TZLOs). The TZLO consists of a central neutron star (NS), with a dense white dwarf (WD) material envelope, which is formed as the aftermath of a WD-NS coalescence. We find that the characteristics of the resultant GRBs depend on whether the TZLO collapses immediately following the WD-NS merger or not. Additionally, the observational properties of the consequent GRBs manifest variations contingent upon whether the collapse of the TZLO results in a magnetar or a black hole. We also show that our model is consistent with the observations of GRB 211211A and GRB 200826A. Specifically, the optical excess in GRB 211211A can be attributed to an engine-fed kilonova, while the supernova bump in GRB 200826A is likely due to the collision between the ejecta and the disk wind shell.

Unified Astronomy Thesaurus concepts: White dwarf stars (1799); Neutron stars (1108); Gamma-ray bursts (629)

1. Introduction

The long-standing two-type origins (Zhang 2011) of gamma-ray bursts (GRBs) have recently been challenged by some newly discovered observations, which added a long GRB could originate from a merger-triggered core collapse (Thöne et al. 2011; Yang et al. 2022), whereas a short GRB can originate from a magnetar giant flare (e.g., GRB 200415A; Yang et al. 2020) or an unusual collapse of a massive star (e.g., GRB 200826A; Ahumada et al. 2021; Zhang et al. 2021). In particular, Zhang et al. (2021) suggested the possibility that the intrinsically short duration of the Type II GRB 200826A can be explained by a progenitor involved with a compact object, such as a white dwarf (WD), which supplies much denser materials to account for the short-accretion timescale to match the observed short duration. However, as pointed out by Zhang et al. (2021), isolated WDs are incapable of producing GRBs; one, therefore, has to invoke a merger process between a WD and one other compact star such as a neutron star (NS) or a black hole (BH). One such combination, which has gained increasing interest in the field, is the WD-NS merger. The WD-involved binaries have long been proposed to serve as GRB central engines (Belczynski et al. 2002; Middleditch 2004); however, less attention has been paid to how they generate short-duration GRBs. Furthermore, Yang et al. (2022) investigated the long GRB 211211A, characterized by extended emission (EE) and the detection of a kilonova signal during its afterglow phase. Contrary to the conventional understanding that long bursts originate from the collapse of massive stars, Yang et al. (2022) propose that this particular burst can be attributed to the merger of compact objects. Yang et al. (2022) argue that the WD-NS merger provides a compelling explanation for the observed features of this burst. The second-brightest gamma-ray burst, GRB 230307A, shares some characteristics with GRB 211211A, such as both are long GRBs with notable excesses in their optical afterglows (Sun et al. 2023; Yang et al. 2024), suggesting that GRB 230307A might also be a product of the WD-NS merger (Wang et al. 2024).

A WD-NS system can follow two paths, depending on the mass ratio between the WD and NS, i.e., q = MWD/MSN. For q < qcrit (qcrit, the critical mass ratio), the WD will fill the Roche lobe slowly and undergo stable mass transfer (SMT). In this case, the WD-NS system will form an ultracompact X-ray binary. For q > qcrit, the WD will be disrupted by the NS and will suffer unstable mass transfer (UMT; Paschalidis et al. 2011). Within the framework of the SMT process, it is difficult to envisage a connection with intense astrophysical burst events like GRBs. However, the WD-NS system, through the UMT process, could potentially result in some violent bursting events (Yang et al. 2022; Zhong et al. 2023). During the disruption...
In this phase, the temperature and density in the middle region of the disk are high and may cause the nuclear burning. Margalit & Metzger (2016) and Zenati et al. (2019) did simulations of the nuclear burning process, and their results showed that $10^{-4} - 10^{-3} M_\odot$ of $^{56}$Ni was formed. Metzger (2012), Fernández et al. (2019), Zenati et al. (2020), and Kaltenborn et al. (2023) provided higher values of around $10^{-3} - 10^{-2} M_\odot$. Bobrick et al. (2022) pointed out that more $^{56}$Ni up to 0.05–0.1 $M_\odot$ was synthesized during the process of massive ONe WD-NS mergers. Contemporary numerical simulations have not yet reached a consensus on the quantity of material expelled in the aftermath of WD-NS mergers. By synthesizing the outcomes of numerical analyses conducted by Fernández et al. (2019), Zenati et al. (2019), and Kaltenborn et al. (2023), it is deduced that approximately 10%–80% of the initial WD mass is ejected. This outflow, which includes small amounts of $^{56}$Ni, gives rise to supernova (SN)-like transients characterized by a rapid evolution and diminished luminosity. The nuclear reaction processes, characteristics of the disk wind, and the nature of transients emanating from these mergers have been extensively discussed by Bobrick et al. (2017), Zenati et al. (2019, 2020), Bobrick et al. (2022), and Kaltenborn et al. (2023). These studies propose that certain atypical transient phenomena, such as Ca-rich transients, faint Type Iax supernovae (SNe), and some faint rapid red transients, may be attributable to WD-NS merger events.

In the case that the mass of WD approaches the Chandrasekhar limit, the orbital period of the WD-NS system becomes very short when the UMT phase starts. In such instances, the NS may not be able to completely disrupt the WD but may plunge into the WD (Yang et al. 2022). After the merger process, the remnant consists of a central NS, a dense WD material envelope, and a disk. This type of celestial body, where an NS occupies the core of a WD, bears a structural resemblance to Thorne–Żytkow objects (TZOs; Thorne & Żytkow 1977). We refer to these as TZIOs (Paschalidis et al. 2011) in our context. These objects exist in a super-Chandrasekhar limit state, and their eventual collapse may potentially trigger the production of GRBs (Yang et al. 2022). The GRBs originating from such progenitors exhibit distinct properties in their prompt emissions and subsequent afterglow emissions, differing from those typically associated with the collapse of massive stars or BH/NS-NS mergers.

In this paper, we propose that the collapse of a TZIO, as the aftermath of a WD-NS merger, can be one of the progenitors of GRBs. We present our physical picture in Section 2 and derive our model’s observable components as a fittable model in Section 3. We then apply our model to the interpretation of two peculiar GRBs in Section 4. A brief summary and discussion follow in Section 5.

### 2. The Physical Picture

Paschalidis et al. (2011) conducted general relativistic hydrodynamics simulations of the WD-NS merger process, with their results suggesting that the post-merger product can be described as a TZIO surrounded by a massive disk system. Subsequent studies by Metzger (2012), Margalit & Metzger (2016), Bobrick et al. (2017), Fernández et al. (2019), Zenati et al. (2019, 2020), Bobrick et al. (2022), and Kaltenborn et al. (2023) also conducted numerical simulations of the WD-NS merger process, yet their findings did not mention the formation of TZIO objects. Although Zenati et al. (2020) posited that the leftover WD material would fall back and envelop the NS to form a spherical structure after the disk evolution concludes, it did not describe this product as a TZIO. Predominantly, these numerical simulation efforts on WD-NS mergers primarily focus on the nucleosynthesis process and the observational effects of outflows produced by disk winds, with the post-merger system’s late-stage evolution still requiring further research. Additionally, current numerical simulations have not yet addressed mergers involving WDs and NSs of extreme masses, which represents a future avenue for simulation efforts.

The formation and collapse of a TZIO is illustrated in Figure 1 and outlined in the following steps:

- a. In a WD-NS system, the WD, with a mass ratio of $q > q_{\text{crit}}$, is poised to commence the transfer of material when its orbit falls within the tidal radius (Figure 1(a)).
- b. The WD is disrupted by the NS, and the system undergoes a UMT. The mass–radius relation of massive WD can be approximately expressed as (Nauenberg 1972; Margalit & Metzger 2016)

$$R_{\text{WD}} \approx 1.0 \times 10^6 \text{ cm} \left( \frac{M_{\text{WD}}}{0.7 M_\odot} \right)^{1/3} \times \left[ 1 - \left( \frac{M_{\text{WD}}}{M_{\text{ch}}} \right)^{4/3} \right]^{1/2},$$

where $M_{\text{ch}}$ is the Chandrasekhar mass, and we take it as $1.45 M_\odot$. We assume a $1.4 M_\odot \times 1.4 M_\odot$ WD-NS binary system. The radius of the WD is $1.7 \times 10^8$ cm. This result is associated with that in Althaus et al. (2005). The radius of Roche lobe is (Eggleton 1983)

$$R_{\text{Roche}} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})} a,$$

where $a$ is the separation of the binary, $q = M_{\text{WD}}/M_{\text{NS}}$ is the mass ratio of the binary. The UMT starts when $R_{\text{WD}} = R_{\text{Roche}}$, implying that $a \approx 4.5 \times 10^9$ cm. Then, the orbital period is $P = 2\pi a^{3/2}/[G(M_{\text{NS}} + M_{\text{WD}})]^{-1/2} \approx 3.1$ s. This phase lasts for three to 10 orbital periods (Paschalidis et al. 2011; Bobrick et al. 2022). During the disruption stage, the elongated WD interacts with itself, producing shocks and heating the material (Zenati et al. 2020; Bobrick et al. 2022). The temperature and density are extremely high at the inner region of the accreting disk, which gives rise to nuclear burning. The simulation results from Bobrick et al. (2022) indicate that a very tiny fraction of material ($\sim 1\%$ of initial WD mass) is dynamically ejected at this stage, whereas their previous simulations (Bobrick et al. 2017), as well as those by Paschalidis et al. (2011), did not show any...
material being dynamically ejected during this phase (Figure 1(b)).

In our analysis, we bifurcate the subsequent processes into two distinct scenarios. In the first scenario, the NS merges into the WD at the post-UMT stage, resulting in a significant gravitational perturbation. This perturbation causes the immediate collapse of the TZIO. In the second scenario, the TZIO formed post-UMT does not undergo an immediate collapse. Instead, it remains stable for a finite cooling time before collapse. The time delay of the collapse implies a divergent evolutionary trajectory. Then, we delve into a detailed discussion of both scenarios. For the first scenario:

c1. Most of the material tidally disrupted remains bound during the UMT process (Paschalidis et al. 2011; Zenati et al. 2020; Bobrick et al. 2022; Kaltenborn et al. 2023). A portion of the WD debris eventually envelops the NS, while the remainder forms a disk orbiting around the remnant (Paschalidis et al. 2011). For the case of $q \approx 1$ that we are discussing, the NS may not disrupt the WD
entirely during the UMT phase and will merge into the WD, resulting in a remnant surrounded by a disk (Yang et al. 2022; Figure 1(c1)). The remnant is composed of WD material wrapped in an NS, and we call it TZIO. Numerical simulations (Paschalidis et al. 2011) have shown that the newborn disk, formed by the WD debris, is about the same size as the Roche limit, with its mass exceeding 50% of the initial WD mass. The TZIO is spherical on account of the rotation and with a little larger scale than the initial WD (Paschalidis et al. 2011). Disregarding the minor portion of material dynamically ejected, the mass of the TZIO consists of the mass of the NS plus a small fraction (e.g., ~30%–50%; Paschalidis et al. 2011) of the initial WD mass. If the hypothesis presented by Yang et al. (2022) in which the WD is not totally disrupted holds true, then the mass of the TZIO would be correspondingly larger. We propose the resultant mass of the TZIO is \( \sim 2.0 M_\odot \). The abrupt impact of gravitational disturbance overcomes the support of electron degeneracy pressure, thermal pressure, and centrifugal force, inducing the envelope’s collapse.

Although WDs are also compact objects, the merger process between a WD and an NS fundamentally differs from that of NS-NS/BH mergers. It more closely resembles the collapse process of a massive star, yet this collapse is distinct from the accretion-induced collapse (Yi & Blackman 1998) associated with a WD accreting material from a companion star. Here, we describe this process as gravitational disturbance-induced collapse (GDIC). The freefall timescale of the GDIC can be roughly written as

\[
\tau_{ff, TZ} \approx \left( \frac{R_{TZ}^3}{GM_{TZ}} \right)^{1/2},
\]

where \( G \) is the gravitational constant, \( R_{TZ} \) is the radius of TZIO. The viscous timescale of the disk is

\[
\tau_{vis} \simeq 16.6 \, s \left( \frac{\alpha}{0.05} \right)^{-1} \left( \frac{H}{R} \right)^{-2} \left( \frac{R}{4.5 \times 10^8 \, cm} \right)^{3/2} \left( \frac{M_{TZ}}{2.0 \, M_\odot} \right)^{-1/2},
\]

where \( \alpha \) is the viscosity constant, \( H \) is the disk thickness, \( R_{\text{disk}} \) is the radius of the disk, and \( M_{TZ} \) is the mass of TZIO.

During the collapse process of the TZIO, the envelope WD material undergoes neutronization, and the forming proto-NS is surrounded by a neutron-rich disk that ejects a portion of neutron-rich material. This ejected material, combined with the dynamical ejecta from the process shown in Figure 1(b), moves as a unified entity (Yang et al. 2022). In Figures 1(d11) and (d12), we use different colors to represent these two distinct sources of ejecta.

d11. If the remnant does not promptly collapse to a BH, the nascent NS, influenced by differential rotation, would generate subsequent high-energy emissions via the magnetic bubble mechanism (Kluźniak & Ruderman 1998; Yang et al. 2022). In this scenario, the GRBs generated are likely composed of two components: the jet produced by the accretion of the disk onto the NS (Zhang & Dai 2009, 2010), and the magnetic bubbles (the helical lines) from the differential rotation of the protomagnetar reveal as EE. The magnetic dipole radiation (the red-wavy lines with arrows) also contributes a certain amount of energy to the ejecta such that an optical excess will be observed during the afterglow phase.

d12. Otherwise, the post-merger object collapses to a BH immediately. In comparison to the scenario of d11, the GRBs produced in this case consist solely of jets generated by the disk accreted onto the BH, without the part produced by magnetic bubbles. Consequently, the observed GRB would be classified as an ordinary long-duration burst devoid of any EE components. Furthermore, due to the absence of an energy supply from magnetic dipole radiation, the optical excess in the ejecta would not be as pronounced as observed in the scenario of d11.

For the second scenario:

c2. The object formed post-merger, which has a mass distribution similar to that in case c1, possesses sufficient outward forces, including electron degeneracy pressure, thermal pressure, and centrifugal force, to balance the effects of its self-gravity. Consequently, the UMT results in a TZIO with a disk that will persist for a certain duration\(^7\) (Figure 1(c2)). Because of the shock heating during the tidal disruption process, the envelope of the newly formed TZIO, as well as the disk, is very hot, with temperatures up to \( 1.5 \times 10^9 \, K \) (Paschalidis et al. 2011). The numerical simulation conducted by Bobrick et al. (2022) unveiled elevated thermal conditions. Specifically, the disk’s midplane is characterized by an assemblage of free nucleons, exhibiting both high-density and temperature conditions that are conducive to the nucleosynthesis of heavy elements, as delineated by Margalit & Metzger (2016). Concurrently, the outflow is accompanied by the formation and evolution of the disk.

d2. During the outflow process, part of the material will be lost in the form of disk wind, forming a shell, as shown in Figure 1(d2). However, there is currently no consensus on how much material is ejected. The results from Zenati et al. (2019) suggest that only a small fraction of the material is ejected, with the majority still bound by the NS. Metzger (2012) and Fernández et al. (2019) indicated that more than 50% of the disk mass is lost. Although Bobrick et al. (2022) did not specify the exact amount of the mass of disk wind, they propose that more than 60% of the disk mass would be ejected. Kaltenborn et al. (2023) believed that the outflow is greatly influenced by the entropy of the disk. If the disk is in a state of high entropy, the proportion of material lost could range from \( \sim 20\%–40\% \) of the initial WD mass, while in a state of low entropy, this proportion could be smaller than 20%.

\(^7\) In fact, dynamical ejecta similar to those in Figure 1(cl) are present in this scenario as well. However, in this case, such ejecta do not produce significant observational effects, and hence, they are not marked in the figure.
Several tens to thousands of seconds after the merger, the mass of the outflow ceases to increase significantly, indicating that the disk wind phase has essentially concluded (Fernández et al. 2019; Zenati et al. 2019). Eliminating the mass loss caused by disk wind, the remaining WD material and the NS together constitute the TZIO. The radius of the TZIO is close to the initial radius of WD (Paschalidis et al. 2011). The mean density of the TZIO envelope is $\rho \sim 1.0 \times 10^{8} \text{ g cm}^{-3}$. For the extreme relativistic condition, the calculated thermal gas pressure to electron degeneracy pressure of the envelope is $P_{\text{th}}/P_{\text{de}} \approx 8.04 \times 10^{-15} n_{k}\beta \left(\rho/\rho_{\text{th}}\right)^{-4/3} \approx 0.61$, where $n$ is the particle number density. We take $T = 3 \times 10^{9} \text{ K}$ here, which is higher than the result presented by Paschalidis et al. (2011) because of the more massive WD in our model. The high-temperature and high-density conditions have reached the critical condition for carbon burning. Zenati et al. (2020) calculated the energy released by thermonuclear burning for $\sim 10^{46}$–$10^{47} \text{ erg}$. We noticed that the WD material at the innermost region was accreted by the NS continuously. The accretion luminosity could be represented by the Eddington luminosity. The thermal energy is $E_{\text{th}} = \frac{16}{3} \pi R_{\text{TZ}}^{3} \sigma T^{4} / c \sim 10^{49} \text{ erg}$. This indicates that nuclear energy has little contribution to the total energy. During this period, there is not significant mass outflow, and the neutrino emission is the dominant cooling mechanism as the system is in high-temperature and high-density conditions (Beaudet et al. 1967). The cooling timescale can be calculated as $\tau_{\text{cooling}} \approx 1.76 \rho_{9} / T_{5}^{2} \text{ yr}$ (Paschalidis et al. 2011). When the temperature is set to be $3 \times 10^{9} \text{ K}$, the cooling timescale is approximately 1 week.

e2. During the process of b, c2, and d2, the magnetic field of the NS would be amplified as accreting materials from the WD (Zhong & Dai 2020). After cooling down, the TZIO eventually begins to collapse (Figure 1(e2)) when the supporting force cannot resist the gravitational force. Such GDIC can naturally lead to a GRB central engine, similar to the WD accreted material. Such GDIC can naturally lead to a GRB central engine, similar to the WD accreted material.

f21. During the collapsing of TZIO, the material of the envelope is neutronized. Part of the neutronized material would be ejected (Yang et al. 2022). The fate of the remnant is similar to d11. If the remnant does not collapse to BH promptly, the ejected material can be further heated by the magnetic dipole radiation of the central magnetar and radiate as an optical bump in observation. Furthermore, the ejected material can also interact with the disk wind shell at a larger radius and produce an additional late-time bump in the optical band.

f22. Otherwise, the remnant rapidly collapses to a BH (although such a case is unlikely, it is not entirely ruled out), and the ejecta cannot be accelerated. The ejecta requires a long time to catch up with the disk wind shell, and due to the ejecta not achieving subrelativistic speed, the collision energy is relatively low, resulting in no significant observable effects.

3. Model of the Afterglow

The remnant of TZIO collapse can exist in either one of two states: a massive magnetar (Figure 1(d11), (f21)) and direct collapse into a BH (Figure 1(d12), (f22)). In the scenario where a BH is formed, the optical afterglow may exhibit an excess due to the decay of heavy elements, potentially produced by the $r$-process within the ejecta, in addition to the standard afterglow. In the scenario where a massive magnetar is formed, the magnetic dipole radiation significantly heats and accelerates the ejecta, leading to more pronounced observational effects in the afterglow. This may include features analogous to those observed in a merger-nova (Yu et al. 2013), as well as components characteristic of an interaction-powered supernova (IPSN). Here, we consider the magnetar scenario, and the observed flux of such emissions can be derived as follows.

The total rotation energy of the newly born twirling magnetar is

$$E_{\text{rot}} = \frac{1}{2} I \Omega^{2},$$

where $I$ is the moment of inertia, and $\Omega$ is angular velocity. The energy loss follows

$$-\frac{dE_{\text{rot}}}{dt} = -I \dot{\Omega} \Omega = \frac{B_{e}^{2} R_{6}^{6} \Omega^{4}}{6 \epsilon^{3}} + \frac{32 G I^{2} \epsilon \Omega^{6}}{5 \epsilon^{5}} = L_{\text{EM}} + L_{\text{GW}},$$

which incorporates electromagnetic luminosity, $L_{\text{EM}}$, and gravitational wave (GW) luminosity, $L_{\text{GW}}$. $B_{e}$ corresponds to the NS surface magnetic field at the pole. $\epsilon$ is the ellipticity of the magnetar. The time derivative of angular velocity can be described as

$$\dot{\Omega} = -k \Omega^{n},$$

where $k$ can be simplified as a constant, and $n$ is the braking index (Lasky et al. 2017). Given that the deformation of the protomagnetar is minimal following the cessation of differential rotation, the contribution of GW radiation can be considered negligible. Following Yu et al. (2013) and Lasky et al. (2017), we set $n = 3$ in this work.

Combining electromagnetic part of Equation (6) with Equation (7), one can easily derive $L_{\text{EM}}$ in the simple form of

$$L_{\text{EM}} = L_{0} \left(1 + \frac{t}{\tau}\right)^{-2},$$

where $L_{0} = 10^{49} R_{6}^{6} B_{e}^{2} P_{15}^{2} P_{-3}^{-4} \text{ erg s}^{-1}$ is the initial luminosity of the magnetar, and $\tau = 2 \times 10^{9} R_{6}^{6} P_{15}^{2} P_{-3}^{2} \text{ s}$ is the spindown timescale of the magnetar. So, $L_{\text{EM}}$ can be regarded as the spindown luminosity of the magnetar, $L_{\text{EM}} = L_{sd}$.

The total energy of the ejecta can be expressed as

$$E_{\text{ej}} = \Gamma M_{\text{ej}} c^{2} + \Gamma E_{\text{int}}^{\text{RF}} + \Gamma^{2} M_{\text{sw}} c^{2},$$

where $\Gamma$ is the Lorentz factor, $E_{\text{int}}^{\text{RF}}$ is the internal energy in the comoving rest frame, $M_{\text{sw}} = 4/3 \pi R^{2} \rho_{0} \rho_{\text{p}}$ is the mass of the swept-up circumburst medium (CBM), and $R$ is the radius of the ejecta.

Assuming a fraction $\xi$ of spindown energy injected into the ejecta, one can calculate that the energy change of the eject is

$$dE_{\text{ej}} = (\xi L_{\text{sd}} - L_{e}) dt,$$
where $L_c$ is the radiated bolometric luminosity.

The dynamical evolution of the ejecta can be written as (Huang et al. 2000; Yu et al. 2013)

$$\frac{d\Gamma}{dt} = \frac{\xi L_{sd} - L_c - D \frac{dE_{\text{int}}^{RF}}{dt}}{M_\text{ej} c^2 + E_{\text{int}}^{RF} + 2\Gamma M_\text{ej} c^2},$$

where $D = 1/\Gamma(1 - \beta)$ is the Doppler factor.

The variation of internal energy of the ejecta in the comoving frame can be written as (Kasen & Bildsten 2010)

$$\frac{dE_{\text{int}}^{RF}}{dt} = \frac{\xi L_{sd} - L_c^{RF} - P_{\text{RF}}^{t} dV_{\text{RF}}}{dt},$$

where the comoving radiation luminosity is $L_c^{RF} = L_c/D^2$.

The last term of Equation (12) represents the work of free expansion. In the comoving frame of the ejecta, the pressure is dominated by radiation, so

$$P_{\text{RF}} = \frac{E_{\text{int}}^{RF}}{3V_{\text{RF}}};$$

and the evolution of the bulk of ejecta is

$$\frac{dV_{\text{RF}}}{dt} = 4\pi R^2 \beta c.$$

By utilizing

$$\frac{dR}{dt} = \frac{\beta c}{1 - \beta},$$

one can write the comoving radiation bolometric luminosity as (Kasen & Bildsten 2010; Kotera et al. 2013)

$$L_c^{RF} = \begin{cases} \frac{E_{\text{int}}^{RF} \Gamma c}{\tau R}, & \tau > 1 \\ \frac{E_{\text{int}}^{RF} \Gamma c}{R}, & \tau < 1, \end{cases}$$

where $\tau = \kappa(M_{\text{ej}}/V^{RF})(R/\Gamma)$ is the optical depth of the ejecta, and $\kappa$ is the opacity.

The dynamical evolution of the ejecta properties, such as $\tau$, $R$, $E_{\text{int}}^{RF}$, and $V^{RF}$, can be solved through Equations (8)–(15).

For any given frequency, $\nu$, the observed specific flux of the ejecta can be calculated as

$$F_{\nu,\text{ej}} = \frac{1}{\max(\tau, 1)} \frac{1}{4\pi D_L^2} \frac{8\pi^2 D^2 \nu}{h c^2 \nu} \frac{(h \nu/D)^4}{\exp(h \nu/D K T^{RF}) - 1},$$

where $D_L$ is the luminosity distance of the burst, $h$ is the Planck constant, $k$ is the Boltzmann constant, and $T^{RF} = (E_{\text{int}}^{RF}/o V^{RF})^{1/4}$ is the comoving temperature.

In addition, the interaction between ejecta and the disk wind shell at a large radius (Figure 1f21) causes a forward shock and reverse shock. Such shocks heat the shell and lead to an IPSN in the optical. Following Chatzopoulos et al. (2012) and the parameterization therein, the output luminosity of the interaction can be expressed semi-analytically as

$$L_{\text{IPSN}} = \frac{1}{t_0} e^{-\frac{t}{t_0}} \int_0^{t'_0} e^{-\frac{t}{t_0}} \left(\frac{2\pi}{n - s}\right)^{3/2} n^2 \left(\frac{n - s}{(n - s)^2 + (n - s)^2}ight) (n - 3)^2$$

$$\times (n - 5) (\beta_F^{5-1} - 1)^{2(n-1)(n-2)}$$

$$\times \theta(t_{FS,BO} - t') + 2\pi \left(\frac{A_{\nu}^q}{q}\right)^{3/2} \beta_R^{5-1} n^p$$

$$\times \left(\frac{3 - 5}{n - s}\right) (n - 5) \left(\frac{n - s}{(n - s)^2 + (n - s)^2}\right) \theta(t_{RS,*} - t') dt'.$$

The final observed flux can be calculated by combining Equations (16) and (17):

$$F(t, \nu, P) = F_{\nu, \text{AG}}(t) + F_{\nu,\text{ej}}(t, t_{0,1}) + \frac{L_{\text{IPSN}}(t, t_{0,2})}{4\pi D_L^2},$$

where $P$ is set free parameters as specified in Section 4.3, $t_{0,1}$ and $t_{0,2}$ are the onset time of the two components. $F_{\nu, \text{AG}}$ includes the standard afterglow component using an external forward shock model following the Python afterglow module (Ryan et al. 2020). Equation (19) can be directly compared with observational data through a Monte Carlo fit (Section 4.3).

### 4. Explanations for Two Peculiar GRBs

#### 4.1. GRB 211211A

The prompt emission of GRB 211211A exhibits a $T_{90}$ of 43.18 s, which can be decomposed into two distinct phases: a main emission (ME) lasting 13 s, followed by EE persisting for 55 s (Rastinejad et al. 2022; Troja et al. 2022; Yang et al. 2022). Subsequent observations have identified a host galaxy for the burst, located at a redshift of $z=0.076$. The characteristics of GRB 211211A align with those typically observed in Type I GRB, including (Yang et al. 2022) (1) minimal spectral lag; (2) the burst has a large offset within its host galaxy, which is consistent with the expected progenitor sites for Type I GRB; (3) the ME comply with the Amati relation for Type I GRB (whereas the EE follows to Type II GRB in the Amati relation diagram); (4) optical excess around 1–10 days post-burst; and (5) the absence of an associated SN component. However, the duration of the prompt emission is characteristic of Type II GRB, which is not typically thought to be produced by binary NS mergers due to the difficulty in sustaining such prolonged emission.

Yang et al. (2022) postulated that GRB 211211A might originate from a WD-NS merger. They suggested that when the mass of WD approaches the Chandrasekhar limit, the NS merger into the WD triggers the remnant to collapse under intense gravitational forces. This collapse is posited to generate the ME of GRB 211211A. The protomagnetar, characterized by its differential rotation, is theorized to produce magnetic bubbles (Kluźniak & Ruderman 1998), which correspond to the observed EE component. The collapse of the TZIO envelope material, being a neutronization process, results in some neutrons incorporated into the ejecta, facilitating the r-
effects of thermal pressure, rapid rotation, and electron degeneracy pressure. The accretion disk formed during the merger rapidly lost a substantial amount of material due to disk wind, leading to the formation of an expanding outer shell. As neutrino radiation continued, the TZIO shed most of its thermal energy, eventually succumbing to internal gravitational forces and collapsing. This collapse process is accompanied by neutronization, resulting in the ejection of neutron-rich material (Yang et al. 2022).

The protomagnetar exhibits significant differential rotation during this process, generating magnetic bubbles that were the source of the prompt emission of GRB 200826A. Subsequently, the magnetar’s dipole radiation accelerated the ejecta, producing radiation characteristics akin to those of a merger nova (Yu et al. 2013). This material accelerated to subrelativistic velocity and eventually caught up with the earlier-formed shell by disk wind, colliding with it and triggering SN-like radiation.

4.3. The Fit

Given that the afterglow of GRB 211211A has been effectively modeled by Yang et al. (2022), this study refrains from replicating that analysis and instead focuses on further modeling the afterglow of GRB 200826A. To do so, we first collect all available observational data of GRB 200826A in the following energy bands:

1. $\gamma$-ray. Following Zhang et al. (2021), GRB 200826A is shown as a short-duration burst with $T_{90} = 0.96^{+0.05}_{-0.08}$ s at 10–800 keV band, with an isotropic energy of $E_{iso} = (7.09 \pm 0.28) \times 10^{51}$ erg.
2. X-ray. Swift/X-Ray Telescope (XRT) skewed in the direction of GRB 200826A at $\sim 6 \times 10^5$ s after the trigger time of Fermi/Gamma-ray Burst Monitor (GBM). The X-ray data are obtained from the Swift/XRT repository9 (Evans et al. 2007, 2009) and are plotted in the middle panel of Figure 2.
3. Optical. The first optical counterpart is obtained by the Zwicky Transient Facility (ZTF) at $\sim 0.2$ days (Ahumada et al. 2020b), and the host galaxy is confirmed with redshift at $z = 0.7481 \pm 0.0003$ (Rothenberg et al. 2020). An optical flare is observed by the Large Binocular Telescope (LBT; Rothenberg et al. 2020) at 2.18 days. We carried out our observations in the $r$ band with the Las Cumbres Observatory Global Telescope (LCOGT) and obtained several upper limits around 2.27 days. Ahumada et al. (2021) reported a series of $i$-band observations from the Gemini-North 8 m telescope and measured an optical bump with $M_i = 25.45 \pm 0.25$ AB mag at $t = 28.28$ days. Rossi et al. (2022) reprocessed the observation and revised it to $M_i = 24.53 \pm 0.21$ AB mag, and they found the other two optical observations. One was observed by LBT at $t = 37.1$ days after the burst with $M_B = 24.06 \pm 0.20$ AB mag. The other is at $t = 46.11$ days, and the magnitude was $M_i = 25.36 \pm 0.26$ AB mag. All those data, as well as those reported in GCN circulars10 by multiple facilities, including the Telescopio Nazionale Galileo (TNG), Gran Telescopio Canarias (GTC), and

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9 https://www.swift.ac.uk/xrt_curves/00021028/
10 https://gcn.gsfc.nasa.gov/other/200826A.gcn3
with the best-fit parameters in Table 2. The priors of the free parameters, as well as their allowed ranges, are listed in Table 2 and plotted in Figure 3. The model predictions using the best-fit parameters are overplotted in Figure 2.

Our model successfully fit the data. The best-fit parameters, as well as their constraints, are listed in Table 2 and plotted in Figure 3. The model predictions using the best-fit parameters are overplotted in Figure 2.

Our fit highlights the following physical constraints of the system:

1. $\xi$. The best-fit value of the energy ejection ratio, $\xi$, is constrained at 0.35$^{+0.18}_{-0.09}$, indicating that one-third of the spindown energy is injected into the ejecta.

2. $\kappa$. Our result shows the opacity of the ejecta is $\kappa = 19.40^{+6.56}_{-4.73}$. Such a large opacity suggests the ejecta should be rich in heavy elements (Yu et al. 2018; Tanaka et al. 2020; Yang et al. 2022), possibly brought by the effect of the neutron capture process.

3. $M_{ej}$. With $M_{ej} = 0.005^{+0.017}_{-0.001}$ $M_{\odot}$, the mass of the ejecta during the collapse of the TZIO is found to be similar to the result of the NS-NS merger simulation (Hotokezaka et al. 2013).

4. $n_{0}$. The interstellar medium density is contained at $11.80^{+10.66}_{-3.03}$ cm$^{-3}$. Such a large value is consistent with the observational fact that the burst is located in the host galaxy with a small offset (Zhang et al. 2021), likely a denser area with a higher star formation rate, yet it allows the possibility of forming a WD-NS system (Toonen et al. 2018; Zhong & Dai 2020).

5. $\theta_{C}$ and $\theta_{obs}$. The jet-core angle and the observer angle are constrained at $\theta_{C} = 12.32^{+1.12}_{-1.55}$ deg and $\theta_{obs} = 4.58^{+3.95}_{-0.21}$ deg, respectively, suggesting an on-axis observation of a typical GRB jet.

6. NS properties. Our fitting results constrain an NS with a magnetic field of $3.40^{+0.70}_{-0.15} \times 10^{15}$ G and a rotating period of $2.63^{+5.59}_{-0.20}$ ms, fully in agreement with the magnetar-powered GRB central engine.

7. A merger-nova-like component. The best fit of our model yields a significant optical bump at $\sim 2$–3 days, as plotted in the top panel in Figure 2.

8. The SN-like optical bump. Our model successfully explained the optical bump as an IPSN with the following key settings in Equation (18): (1) compact profile $n = 5.1$. (2) The power-law exponent for the CBM shell density profile $s = 2$. (3) The mass of the disk wind shell is set to $M_{S} = 0.5 M_{ej}$. Assuming the maximum velocity of the disk wind to be $5 \times 10^{3}$ cm s$^{-1}$ (Zenati et al. 2020; Bobrick et al. 2022), we derive the mean density of the disk wind shell to be $\rho_{S} = 3 \times 10^{-7}$ g cm$^{-3}$ 10 days after the merger. (4) The radius when the ejecta collides with the disk wind shell is at $3 \times 10^{14}$ cm. (5) The optical depth of the disk wind shell is $\tau_{Thomson} \approx \kappa_{0}M_{ej}/4\pi R^{2} > 1$, where $R$ is the radius of the disk wind shell and $\kappa_{0}$ is the Thomson scattering opacity of the disk wind shell, which is set to $\kappa_{0} = 0.4$ cm$^{-2}$ g$^{-1}$. We notice that $R \approx 4.4 \times 10^{13}$ cm meets the optically thick condition.

### 4.4. Interpretation of the Disparate Properties of the Two Bursts

Our model operates within the framework of a massive WD-NS merger, where delayed collapse leads to distinct properties of the two GRBs and follow-up observations.

1. In the first scenario, GRB 211211A is produced with a long-duration ME accompanied by EE, whereas GRB...
200826A is likely a product of the second scenario, characterized by a short duration. For GRB 211211A, the characteristic timescale of the ME is decided by the viscous timescale of the accretion disk, while the EE results from the differential rotation of the post-collapse magnetar, which generates magnetic bubbles that burst forth.

In the case of GRB 200826A, the delayed collapse allows for the evaporation of the accretion disk formed during the merger, with the GRB arising solely from the eruption of magnetic bubbles. The NS at the core of the TZIO continuously accretes envelope material prior to the collapse, thereby amplifying its magnetic field (Zhong & Dai 2020). This process results in a reduced timescale for magnetic bubble generation compared to that of GRB 211211A. If this process amplifies the surface magnetic field of the NS within the TZO to $5 \times 10^{14}$ G, the interval time for the generation of magnetic bubbles would be approximately 0.03 s. Under the same differential kinetic energy ($E_\text{d}$) and speed ($\Delta \Omega$; e.g., $E_\text{d} \approx 3 \times 10^{51}$ erg and $\Delta \Omega \approx 10^4 \text{s}^{-1}$) as assumed in Yang et al. (2022), the duration of the magnetic bubbles would decrease to about 1 s, consistent with the prompt emission timescale observed in GRB 200826A.

2. Typically, long and short GRBs fall into their respective regions on the Amati relation diagram. However, plotting these two GRBs on the Amati relation diagram reveals some peculiarities. The ME of GRB 211211A is located at the site of Type I GRBs in the Amati relation, while the EE aligns with the site of Type II GRBs (see Figure 2b of Yang et al. 2022). GRB 200826A, although classified as a short burst, is positioned within the Type II GRB category (see Figure 2(a) of Zhang et al. 2021). This could be attributed to the similar origins of the EE of

### Table 1

| $t_\text{obs}$ (day) | Telescope                  | Band | System  | Magnitude | Flux Density ($\mu$Jy) | References |
|---------------------|---------------------------|------|---------|-----------|------------------------|------------|
| 0.21                | ZTF                       | g    | AB      | 20.86±0.04 | 16.44±0.62             | (1)        |
| 0.23                | ZTF                       | r    | AB      | 20.70±0.05 | 19.05±0.99             | (1)        |
| 0.28                | ZTF                       | g    | AB      | 20.96±0.16 | 15.00±2.38             | (1)        |
| 0.77                | Kitab-ISON RC-36          | CR   | AB      | >20.2     | <30.30                 | (3)        |
| 1.15                | ZTF                       | g    | AB      | 22.75±0.26 | 2.88±0.41              | (1)        |
| 1.21                | ZTF                       | r    | AB      | >21.30    | <10.96                 | (1)        |
| 1.29                | ZTF                       | g    | AB      | >21.20    | <12.02                 | (1)        |
| 1.74                | Kitab-ISON RC-36          | CR   | AB      | >20.4     | <25.12                 | (3)        |
| 1.79                | Swift/UVOT                | White/(170–650 nm) | AB | 21.86±0.13 | 8.55±0.74              | (2)        |
| 2.18                | LBT                       | g    | AB      | 24.08±0.19 | 0.85±0.14              | (5)        |
| 2.18                | LBT                       | r    | AB      | 23.39±0.16 | 1.60±0.22              | (5)        |
| 2.27                | LCOGT                      | r    | AB      | >23.30    | <1.79                  | (9)        |
| 2.28                | LCOGT                      | g    | AB      | >23.41    | <1.57                  | (9)        |
| 3.23                | LDT                       | r    | AB      | 24.46±0.12 | 0.60±0.07              | (4)        |
| 3.99                | GTC                       | r    | AB      | 24.51±0.14 | 0.57±0.08              | (8)        |
| 28.28               | Gemini-North 8 m telescope/GMOS-N | i   | AB      | 24.53±0.21 | 0.56±0.12              | (7)        |
| 28.28               | Gemini-North 8 m telescope/GMOS-N | r   | AB      | >25.6     | <0.21                  | (7)        |
| 31.9                | TNG telescope             | r    | AB      | >25.3     | <0.27                  | (6)        |
| 37.1                | LBT telescope/LUCI        | H    | AB      | 24.06±0.20 | 0.86±0.17              | (6)        |
| 46.11               | Gemini-North 8 m telescope/GMOS-N | i   | AB      | 25.36±0.26 | 0.26±0.07              | (7)        |
| 46.11               | Gemini-North 8 m telescope/GMOS-N | r   | AB      | >25.5     | <0.23                  | (7)        |
| 72.05               | LCOGT network observatory | i    | AB      | >22.7     | <3.02                  | (9)        |
| 72.48               | Lijiang 2.4 m telescope   | g    | AB      | >22.58    | <3.37                  | (9)        |
| 72.48               | Lijiang 2.4 m telescope   | r    | AB      | >22.07    | <5.40                  | (9)        |
| 72.48               | Lijiang 2.4 m telescope   | i    | AB      | >21.81    | <6.85                  | (9)        |

### References.

(1) GCN Circular 28295 (Ahumada et al. 2020), (2) GCN Circular 28300 (D’Ai et al. 2020), (3) GCN Circular 28306 (Belkin et al. 2020), (4) GCN Circular 28312 (Dichiara et al. 2020), (5) GCN Circular 28319 (Rothberg et al. 2020), (6) GCN Circular 28949 (Rossi et al. 2020), (7) GCN Circular 29029 (Ahumada et al. 2020a), Rossi et al. (2022), (8) Rossi et al. (2022), (9) This work.
GRB 211211A and the prompt emission of GRB 200826A, which share comparable spectral properties.

3. No SN component was observed in association with GRB 211211A, whereas SN features were detected for GRB 200826A. This is because GRB 211211A triggered an immediate collapse following the WD-NS merger, while GRB 200826A experienced a delayed collapse after the merger. Before the collapse, a shell was formed by the disk wind on the outside (Figure 1(d2)). Ultimately, cooling led to the collapse of the TZIO, and the ejecta, accelerated to subrelativistic speed, collided with the shell, producing optical radiation akin to that of an SN.

5. Summary and Discussion

In this paper, we have introduced the collapse of TZIO as one of the progenitors of GRBs. In our discussion, there are two distinct scenarios of the collapse of a TZIO. In the first scenario, the TZIO undergoes immediate collapse post-formation. Due to the presence of a large-scale accretion disk generated during the merger process, the resulting GRB exhibits a long duration. Post-collapse, the object can evolve in two ways: if the TZIO collapses into a massive magnetar, it may produce a GRB similar to GRB 211211A. If the TZIO collapses directly into a BH, the resulting GRB will...
be a general long burst without an extended emission component.

In the second scenario, the TZIO, existing beyond the Chandrasekhar limit, is initially sustained by outward forces, allowing it to survive for a period. The accretion disk formed during the merger evaporates in the form of disk winds, creating an outward-moving shell composed of disk material. As neutrino radiation carries away most of the thermal energy, the system eventually succumbs to its intense self-gravity and collapses inward. There are two possibilities regarding the remnant fate of the TZIO: one is that the TZIO does not collapse directly to a black hole but remains as a massive remnant due to the limited freefall time of the collapsing material, or it could collapse directly to a black hole but remains as a massive remnant due to the limited freefall time of the collapsing material.

The event rate of WD-NS mergers is \(0.5 \times 10^4 \text{ Gpc}^{-3} \text{yr}^{-1}\) (Thompson et al. 2009; Paschalidis et al. 2011), or as low as \(0.7 \times 10^4 \text{ Gpc}^{-3} \text{yr}^{-1}\) in the near cosmos (Liu 2018). A non-negligible fraction of these mergers can undergo the UMT process (Bobrick et al. 2017), while the formation of TZIOs is contingent upon the presence of WDs with significantly high masses. WDs exceeding a mass of 1.3 \(M_\odot\) are estimated to constitute a mere 0.5% of the total WD population (Kepler et al. 2007). This rarity substantially limits the formation rate of TZIOs to \(\sim 50 \text{ Gpc}^{-3} \text{yr}^{-1}\). Furthermore, considering the beaming effect of GRBs and applying a beaming factor of 0.01, the resultant event rate of GRBs originating from TZIO collapses is estimated to be \(\sim 0.35 \times 0.5 \text{ Gpc}^{-3} \text{yr}^{-1}\).

The GW emission from WD-NS mergers presents distinct characteristics compared to those from binary NS mergers and the collapse of massive stars. In the scenario of a merger involving a massive WD and an NS, the onset of mass transfer occurs as the WD fills its Roche lobe when the orbital period is approximately 3 s, corresponding to the frequency of GW emissions at around 0.1–1 Hz (Kang et al. 2024). This falls within the detection range of future space-based GW detectors.

Due to the beamed nature of GRBs, observations of coincident GWs and GRBs are not always expected in WD-NS mergers. However, optical emissions are present, particularly in scenarios involving delayed collapse. In such cases, the stellar wind shell may contain radioactive materials like \(^{56}\text{Ni}\), potentially leading to low-luminosity SNe, such as SNe Iax, faint rapid transients, or Ca-rich transients (Zeni et al. 2020; Bobrick et al. 2022; Kaltenborn et al. 2023). If the TZIO does not immediately collapse into a black hole but instead forms a massive magnetar, the interaction between the magnetar-driven ejecta and the disk wind shell can produce an IPSN. The production of an IPSN and a GRB also involves a temporal delay, marking another distinction from typical SNe associated with GRBs.

Nevertheless, discoveries of similar events in the future or the existing GRB samples can shed some light on this new class of GRB events and the fate of the WD-NS mergers.

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