QUARK-NOVAE IN LOW-MASS X-BINARYs. II. APPLICATION TO G87−7 AND TO GRB 110328A

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Received 2011 May 15; accepted 2011 September 2; published 2011 November 29

ABSTRACT

We propose a simple model explaining two outstanding astrophysical problems related to compact objects: (1) that of stars such as G87−7 (alias EG 50) that constitute a class of relatively low-mass white dwarfs (WDs) which nevertheless fall away from the C/O composition and (2) that of GRB 110328A/Swift J164449.3+57345 which showed spectacularly long-lived strong X-ray flaring, posing a challenge to standard gamma-ray burst models. We argue that both these observations may have an explanation within the unified framework of a quark-nova (QN) occurring in a low-mass X-ray binary (LMXB; neutron star (NS)–WD). For LMXBs, where the binary separation is sufficiently tight, ejecta from the exploding NS triggers nuclear burning in the WD on impact, possibly leading to Fe-rich composition compact WDs with mass $0.43 M_\odot < M_{WD} < 0.72 M_\odot$, reminiscent of G87−7. Our results rely on the assumption, which ultimately needs to be tested by hydrodynamic and nucleosynthesis simulations, that under certain circumstances the WD can avoid the thermonuclear runaway. For heavier WDs (i.e., $M_{WD} > 0.72 M_\odot$) experiencing the QN shock, degeneracy will not be lifted when carbon burning begins, and a sub-Chandrasekhar Type Ia supernova may result in our model. Under slightly different conditions and for pure He WDs (i.e., $M_{WD} < 0.43 M_\odot$), the WD is ablated and its ashes raining down on the quark star (QS) leads to accretion-driven X-ray luminosity with energetics and duration reminiscent of GRB 110328A. We predict additional flaring activity toward the end of the accretion phase if the QS turns into a black hole.

Key words: binaries: close – gamma-ray burst: general – stars: evolution – stars: neutron – supernovae: general – white dwarfs

1. INTRODUCTION

In a recent paper by Ouyed et al. (2011), hereafter OSJ, we presented a detailed account of the quark-nova (QN) model as applied to short gamma-ray bursts (GRBs). The jist of this model is that a QN, which is an explosive transition of a neutron star (NS) to a quark star (QS), when it occurs in a low-mass X-ray binary (LMXB; see Section 2.1 below), can heat and ablate the white dwarf (WD) companion leading to the observed extended X-ray flaring. In this work, we use aspects of the same (OSJ) model to explain the long-lived X-ray flaring seen in GRB 110328A and in the process find a possible resolution for a longstanding puzzle regarding WD compositions. The puzzle is this: there is present no clear scenario that can explain the formation of a low-mass WD with a heavy core composition, including the possibility of an iron core. Provencal et al. (1998) found a handful of such stars using Hipparcos parallax data which do not fall on the expected C/O relationships for average mass WDs. This includes the most outstanding case, that of G87−7 (alias EG 50), which appears to fall instead right on the Hamada & Salpeter (1961) zero-temperature curve for Fe in the M-R plane (see Figure 3 of Provencal et al. 1998).

Before we present numerical estimates to support our arguments below, we emphasize that the crucial of our reasoning can be stated simply: for tight binary separation at the moment the QN happens, ejecta from the NS impacts the WD leading to burning of the C/O WD up to iron, while lifting the degeneracy, leading to stable but “anomalous” WD compositions instead of a Type I supernova (SN). If the WD is light enough, thermal ablation and subsequent accretion of WD material onto the QS occurs. This leads to an accretion-powered X-ray luminosity distinguished by features (energetics, timescale, and temporal variability) reminiscent of GRB 110328A (Cummings et al. 2011).

The paper is organized as follows: in Section 2, we describe the binary configuration in our model and estimate the conditions that determine the fate of the WD (ablated or not). In Section 3, we apply our model to G87−7 and in Section 4 to GRB 110328A. In both cases, we discuss predictions of our model that can be tested. We conclude in Section 5.

2. QUARK-NOVA IN AN LMXB

When matter in the core of a NS reaches the quark deconfinement density, a phase transition to quark matter can occur. Preliminary numerical simulations hint at potential instabilities that can trigger a detonative transition (Niebergal et al. 2011). Ouyed et al. (2002) termed this a “quark-nova” and its likely outcome is the ejection of the outermost layers of the NS, with kinetic energy of the relativistic QN ejecta $E_{QN}^K = (\Gamma_{QN} - 1)M_{QN}c^2 \sim 10^{52}$ erg for typical ejected mass of $M_{QN} \sim 10^{-3} M_\odot$ and ejecta’s Lorentz factor $\Gamma_{QN} \sim 10$ (see Keränen et al. 2005).

2.1. The Binary Configuration

In our model, a QN would form after the first accretion phase, when the increase in central density is driven by spin-down and/or gravitational wave emission (e.g., Staff et al. 2006; see also Staff et al. 2011 for spin-down induced by gravitational waves). In fact, the QN has a higher probability of
occurrence after the first accretion phase since the mass of the NS in such a case would be higher. Furthermore, gravitational wave emission can spin the star down faster than magnetic braking (Staff et al. 2011), causing a large change in the central density. We also note that, in principle, the QN could also occur in the second accretion phase after the WD has reached its Roche lobe (RL). In summary, the QN could occur under three situations in these systems, depending on the initial mass of the NS: (1) during the first accretion phase; (2) from spin-down, caused by a combination of gravitational waves and magnetic braking, following the first accretion phase; and (3) in the second accretion phase.

In the scenario (3), the (C–O or He) WD would fill its RL and the second accretion phase starts. This scenario is reminiscent of ultracompact X-ray binaries (UCXBs). These are binaries with orbital periods shorter than ~1 hr and are believed to be a subset of the LMXBs. Evidence was found for carbon/oxygen as well as helium/nitrogen discs and no evidence for (traces of) hydrogen in some UCXBs (e.g., Nelemans et al. 2006 for a discussion). This suggests that the donors in the observed systems are degenerate WDs. In some of these, only carbon and oxygen lines were identified, which supports the notion of CO WD donors (e.g., Juet et al. 2001). Recent studies concludes that an important fraction of LMXBs may be ultracompact (e.g., in’t Zand et al. 2005). Obviously a thorough population synthesis is needed to address the contribution to UCXBs from systems with non-degenerate, semi-degenerate, and degenerate donors. In general, we favor scenarios/options (2) and/or (3) in our model.

If a QN happens in a binary system with a WD and a NS orbiting each other, what will be the fate of the WD?

2.2. Fate of the White Dwarf

In the paper OSJ, we found that depending on the binary separation, \( a \), the impact of the ejecta with the WD triggers various nuclear burning processes in the latter. The temperature per nucleon of the shocked WD is

\[ k_B T_{\text{WD}} \sim 17.6 \text{ keV} \frac{\mu_{\text{WD}}^2 E_{\text{KE}}^{\text{QX,52}}}{a_{10}^2 M_{\text{WD,0.43}}^{5/3}}, \]

where \( \mu_{\text{WD}} \) is the mean molecular weight in units of 2 (for a CO WD), the WD mass is in units of 0.43 \( M_\odot \) (chosen a posteriori since 0.43 \( M_\odot \) turns out to be the border between ablation and survival of the WD) and the binary separation \( a_{10} \) is in units of 10^{10} cm. Considering CO WDs, we see that for carbon–carbon burning to start (Lang 1980), the temperature must exceed ~70 keV. This implies

\[ a_{10}^2 M_{\text{WD,0.43}}^{5/3} < 0.25 \mu_{\text{WD}}^2 E_{\text{KE}}^{\text{QX,52}}, \]

or in other words the separation must be \( a_{10} < 0.5 \) in order for the temperature to be sufficiently high that carbon–carbon burning can occur in a 0.43 \( M_\odot \) CO WD. We note that this is still larger than the separation at which the WD begins to overflow its RL:

\[ a_{\text{RL}} \sim 9.2 \times 10^9 \left( \frac{M_T}{M_\odot} \right)^{2/3} \left( \frac{0.1 M_\odot}{M_{\text{WD}}} \right), \]

which is 3.7 \times 10^9 cm for a 0.43 \( M_\odot \) WD and a 1.8 \( M_\odot \) NS (\( M_T = M_{\text{NS}} + M_{\text{WD}} \)).

Nuclear burning results in a total energy release \( \sim 4 \times 10^{50} \times M_{\text{WD,0.43}} \Delta_{0.5} \) erg, where \( \Delta_{0.5} \) is the energy gained per baryon due to nuclear burning in terms of 0.5 MeV/baryon. We estimate that the processed nuclei are then ejected at speeds

\[ v_{\text{nuc,ejec}} \approx 3.1 \times 10^3 \text{ km s}^{-1} \eta_{0.1}^{1/2} \Delta_{0.5}^{1/2}, \]

where \( \eta \) is the nuclear-to-kinetic-energy conversion efficiency, taken to have a fiducial value of 0.1. The WD escape speed is \( v_{\text{WD,esc}} \approx 3.2 \times 10^3 \text{ km s}^{-1} \times M_{\text{WD,0.43}}^{3/5} \) using the WD equation of state as given in Equation (2) of OSJ. Thus, the condition for the processed material to escape the WD (ablation) \( v_{\text{nuc,ejec}} > v_{\text{WD,esc}} \) implies

\[ M_{\text{WD}} < 0.43 M_\odot \eta_{0.1}^{3/4} \Delta_{0.5}^{3/4}. \]

The sufficient condition for the WD to burn and be ablated is given by combining Equations (2) and (5). Note that Equation (5) provides a necessary condition for ablation of the WD mass (for a given \( \eta \) and \( \Delta \)). We can write the condition in Equation (2) in terms of a maximum binary separation for a given WD mass:

\[ a_{10} < a_{10}^{\text{max}} = 0.5 \mu_{\text{WD}}^2 E_{\text{KE}}^{\text{QX,52}}^{1/2} M_{\text{WD,0.43}}^{-3/5}. \]

The condition for the WD to burn without ablation follows simply by reversing the inequality in Equation (5) while retaining Equation (2),

\[ 0.43 M_\odot \eta_{0.1}^{3/4} \Delta_{0.5}^{3/4} < M_{\text{WD}} < 0.18 M_\odot \mu_{\text{WD}}^2 E_{\text{KE}}^{\text{QX,52}}^{3/5} a_{10}^{6/5}. \]

From the consistency check that the upper bound in Equation (7) exceeds the lower bound, we obtain \( a_{10} < 0.5 \) for fiducial values\(^5\) of \( \mu_{\text{WD}}, E_{\text{KE}}^{\text{QX}}, \eta, \Delta \) for a CO WD (implying that \( \mu_{\text{WD}} = 2 \)). The resulting WD should be rich in elements heavier than C and O (see Section 3.1). The fate of the WD ashes in the ablation case is explored in Section 4. If the QN happens in an LMXB with \( M_{\text{WD}} > 0.43 M_\odot \) when the binary separation is \( a > a_{10}^{\text{max}} \), it will not lead to nuclear burning in the WD, but such a system should have distinct signatures as the heated WD (with \( kT_{\text{WD}} < 70 \text{ keV} \)) should cool in softer X-rays compared to the case of tight binaries. The different regimes are summarized in Table 1 and applied to particular observational cases in the following sections.

2.3. Pure He WD

A CO WD can be heavy enough to escape ablation, but we show below that a pure He WD most likely cannot. For a pure He WD, \( \mu_{\text{WD}} = 4/3 \), and its temperature must exceed 8.6 keV

\[^4\] The number of baryons in a 0.43 \( M_\odot \) WD is \( n_{\text{baryons}} = M_{\text{WD}}/m_\text{H} \approx 5.1 \times 10^{50} M_{\text{WD,0.43}} \). Nuclear burning releases \( E_{\text{nuc,ejec}} = n_{\text{baryons}} \times \Delta \approx 4.1 \times 10^{50} \text{ erg} M_{\text{WD,0.43}} \Delta_{0.5} \), where the energy released per baryon is parameterized by \( \Delta_{0.5} \) given in units of 0.5 MeV. If 10% (\( \eta = 0.1 \)) of this energy is converted to kinetic energy (i.e., 0.5 \( M_{\text{WD}} v_{\text{nuc,ejec}}^2 = \eta E_{\text{nuc,ejec}} \)) then, the WD nuclei gain a speed of \( v_{\text{nuc,ejec}} \approx 3.1 \times 10^3 \text{ km s}^{-1} \eta_{0.1}^{1/2} \Delta_{0.5}^{1/2} \).

\[^5\] This bound on \( a_{10} \) is the same as \( a_{10}^{\text{max}} \) since checking the consistency of the bounds in Equation (7) is the same as saturating the bound in Equation (5).
in order to start burning Helium in the triple-\(\alpha\)-process. This implies that
\[ a_{10}^2 M_{\text{WD},0.25}^{5/3} < 3.37 \mu_{\text{WD},4.3} E_{\text{KE},0.52}^{5/3}, \tag{8} \]
where the WD mass is units of 0.25 \(M_{\odot}\).

Nuclear burning of helium through the triple-\(\alpha\)-process results in a total energy release of \(\sim 2.4 \times 10^{30} \times E_{\text{KE},0.52}^{5/3} \Delta v_{10}^{3/4} \Delta v_{0.5}^{1/4} \) erg. This leads to the same nuclei speed as before, since that is independent of the WD mass:
\[ v_{\text{nuc,exec.}} \simeq 3.1 \times 10^3 \text{ km s}^{-1} \eta_{0.1}^{1/2} \Delta v_{0.5}^{1/2}, \tag{9} \]
hence inequality (5) also remains the same. However, the mass of a pure He WD is unlikely to be as large as 0.43 \(M_{\odot}\Delta v_{0.5}\) unless \(\eta\) or \(\Delta v\) are much less than their fiducial values of 0.1 and 0.5, respectively. Hence, we expect a pure He WD to ablate in most cases. The maximum binary separation that allows for burning of the He WD is
\[ a_{10} < a_{10}^{\text{max}} = 1.84 \frac{\mu_{\text{WD,4.3}} E_{\text{KE},0.52}^{5/6}}{M_{\text{WD},0.25}^{5/6}}. \tag{10} \]

For completeness, although this is unlikely to happen for a pure He WD, we write down the condition for burning without ablation:
\[ 0.43 M_{\odot} \eta_{0.1}^{3/4} \Delta v_{0.5}^{3/4} < M_{\text{WD}} < 0.52 M_{\odot} \frac{\mu_{\text{WD,4.3}}^{3/5} E_{\text{KE},0.52}^{3/5}}{a_{10}^{6/5}}. \tag{11} \]

3. A CASE FOR G87–7

Following the conclusions of Provencal et al. (1998), the idea that G87–7 could have an Fe core subsequently gained additional support from the work of Panei et al. (2000) who considered detailed evolutionary calculations based on iron core models. The fact that G87–7 is not a massive star by WD standards makes it hard to understand how it could be made of iron or iron-rich material. Mathews et al. (2006) made a systematic study of correction terms to the WD equation of state, but none of these corrections, not even possible effects of magnetic fields can be reasonably varied to fit these compact WDs for a normal He, C, or Mg WD.

Recent measurements by Hipparcos present observational evidence supporting the existence of some WD stars with iron-rich core composition. Cores made of C, O, Ne, Mg, Si, S, and Ca appear to be excluded in favor of cores made of Ar, Ti, Cr, or Fe (or mixtures of those), and hydrogen envelopes that may be thick or thin (see Equation (3)). Specifically, Fontaine et al. (2007) concluded that the derived mass and radius for G87–7 vary in small ranges, from 0.5096 \(M_{\odot}\) (0.0109 \(R_{\odot}\)) for the Ar core model with a thick H envelope to 0.5493 \(M_{\odot}\) (0.0113 \(R_{\odot}\)) for the Fe core model with a thick H envelope. The existence of WDs consistent with an iron core relies critically on the accuracy of atmospheric parameters deduced from optical spectroscopy, e.g., follow-up and improved observations showed that a few of the exotic WDs found by Provencal et al. (1998) were in fact made of carbon–oxygen material (Provencal et al. 2002). Other objects they found show hints of iron mixed with carbon such as Procyon B, which, according to Provencal et al. (2002) is a rare DQZ WD. There remain some candidates that are iron-rich (pending future observations) which are relevant to this work. It is our model prediction, as we show in this work, that if QNe occur in a NS-WD systems, under the right circumstances, iron-rich low-mass WDs could form.

Standard WD formation scenarios do not easily account for such objects (e.g., Isern et al. 1991). As best summarized in Mathews et al. (2006): “The conditions necessary to burn white-dwarf material to iron require such high densities and rapid reaction rates that it would seem impossible to fine tune the parameters of an accreting WD to avoid the thermonuclear runaway associated with a Type-Ia supernova and disruption of the star” (i.e., degenerate conditions prevent controlled burning and causes a thermonuclear runaway because a temperature increase does not lead to a pressure increase).

In what might be called the standard model for a SN Ia, a CO WD accretes matter until it compresses to the point that carbon is ignited just before the Chandrasekhar limit (Mazzali et al. 2007). Although the WD may have a “simmering” phase of order a thousand years following unstable carbon ignition, where thermonuclear runaway is prevented by convection (Piro & Chang 2008), ultimately, explosive burning is ignited and the WD is incinerated in seconds.

The Fermi energy of a WD close to the Chandrasekhar limit is \(\sim 175\) keV, much larger than the carbon ignition temperature, thus burning is induced under degenerate conditions and leads to a thermonuclear runaway and the explosion. On the other hand, in our model, the small WD mass implies that the WD Fermi energy is only around 35 keV. The temperature induced by the QN shock can be comparable to or larger than this, which lifts the degeneracy as it passes through the star. We find that

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**Table 1**

Burning Regimes in our Model

| \(M_{\text{WD}}\) | \(a_{10}\) | \(T_{\text{WD}}\) | Nuclear Burning \(^a\) | Products | Ablation | Binary Disruption |
|----------------|--------|----------------|-----------------|---------|---------|------------------|
| <0.43          | <\(a_{10}^{\text{max}}\) | >8.6 keV       | Partial/complete \(\alpha\)-burning | \(\alpha\)-elements | Yes     | Yes (isolated QS) |
| 0.43–0.72      | <\(a_{10}^{\text{max}}\) | >70.0 keV      | \(\alpha\)-burning | O, Ne, Mg | No     | No               |
| 0.43–0.72      | <\(a_{10}^{\text{max}}\) | >70.0 keV      | Not possible     | None     | No     | No               |
| >0.72          | <\(a_{10}^{\text{max}}\) | >70.0 keV      | Degenerate \(\alpha\)-burning | O, Ne, Mg | Yes     | Yes (isolated QS) |

**Notes.**

\(^a\) For a CO WD, in cases when \(a < a_{\text{RL}}\) (see Equation (3)), oxygen burning and possible nuclear statistical equilibrium can lead to nuclear burning all the way to Fe-group elements.

\(^b\) The velocity impacted by the QN ejecta to the WD is negligible. However, kicks from an asymmetric QN explosion might enhance or suppress the disruption depending on geometry. Thus, isolated \(\alpha\)-elements-rich WDs are not entirely ruled out in our model.
for WD masses $0.43 \, M_\odot \leq M_{\mathrm{WD}} < 0.7 \, M_\odot$, the QN shock is strong enough that $k_{\mathrm{F}} T_{\mathrm{WD}}$ exceeds the Fermi energy.

This scenario is unlike the standard near-Chandrasekhar mass WD responsible for Type Ia SN explosions, where heating does not relieve the degeneracy pressure.

Mathews et al. (2006) have proposed that the outliers found by Provencal et al. (1998), could be made, in part, of strange matter. Such objects would contain a tiny nucleus of strange matter and are known as strange dwarfs (Glendenning et al. 1995). Their masses fall in the approximate range $10^{-4}$ to $1$ solar mass. Structurally, they show a much higher centrally condensed structure than an ordinary WD, and exhibit a smaller radius for a given mass than that expected from C/O cores (see Matsuzaki & Kobayashi (2007) for the stability of these objects). By following the recipe provided in Mathews et al. (2006), Fontaine et al. (2007) were able to construct a model of G87–7 that satisfies both the spectroscopic constraint imposed on the surface gravity and the parallax constraint. They favored a strange WD with a mass of $0.5359 \, M_{\odot}$ (7% of which is due to the strange matter nucleus), a radius of $0.0112 \, R_{\odot}$. They concluded that it is possible to interpret G87–7 in a way that does not invoke heavy element cores.

In any case, the interpretation of iron-core WDs is difficult to achieve from a conventional stellar evolution standpoint and does not fit the observed compact population within a single curve. The strange WD model requires quark matter to be somehow seeded or trapped in the core. Below we offer an alternate explanation based on our LMXB numbers that can naturally account for iron WD without appealing to the strange WD model.

3.1. G87–7 in our Model

According to our model described in Section 2 and summarized in Table 1, a QN occurring in an LMXB with $M_{\mathrm{WD}} > 0.43 \, M_\odot$ when $a_{10} < a_{10}^\mathrm{eq}$, most likely leads to controlled nuclear burning of the WD material without ablation. The Fermi energy of the WD is $E_{\mathrm{F}} \sim 35 \, \text{keV} \times M_{\mathrm{WD},0.134}$. This means that degeneracy is lifted for $0.43 \, M_\odot < M_{\mathrm{WD}} < 0.72 \, M_\odot$ whenever burning conditions ($k_{\mathrm{F}} T_{\mathrm{WD}} > 70 \, \text{keV} > E_{\mathrm{F}}$) are met. Lifting the degeneracy leads to “deflagration” rather than the runaway burning instability (the “detonation” that plagues standard explanations of such exotic WD is effectively shut off). For the stable carbon burning case, the WD mass is below the minimum mass ($\sim 0.7 \, M_\odot$) required to sustain carbon burning in chemically homogeneous main-sequence carbon stars (Deinzer & Salpeter 1965). Instead, in our model we expect the WD to puff up quickly before it cools and shrinks back to a degenerate configuration forming the iron-rich WD. During burning, a $0.575 \, M_{\odot}$ WD, for example, will puff up to a radius of $\sim 3.5 \times 10^8 \, \text{cm}$ from an initial radius of $\sim 1.1 \times 10^8 \, \text{cm}$ thus more than tripling its size. The WD final radius is slightly below the maximum separation that allows for carbon burning (Equation (6)), and therefore the QS may or may not be engulfed by the puffed up WD. If the QS ends up engulfed in the puffed up star, this may lead to a phenomena “a la Thorne–Zytkow” (Thorne & Zytkow 1977). We expect two plausible outcomes of the engulfed QS once it starts sinking into the depth of the puffed up WD: it will either become a black (BH) hole or, form a single star by coalescing with the core of the WD. This aspect of our model will be explored in detail elsewhere. Let us simply add that for the heaviest WD ($M_{\mathrm{WD}} > 0.72 \, M_\odot$), degeneracy will not be lifted when carbon burning begins, and a sub-Chandrasekhar Type Ia SN may result.

From Equations (1) and (3), it is clear that the smaller the WD separation at the time of the QN, the larger the temperature to which it is heated. One plausible maximum temperature the WD can be heated to is $\sim 134 \, \text{keV}$, when the separation equals $a_{\mathrm{RL}}$ given in Equation (3). This is for a CO WD with mass of about $0.6 \, M_\odot$. Although not hot enough for oxygen burning, neon burning can occur; therefore after burning ceases the WD will be composed of a mix of oxygen, neon, and magnesium. Another possibility arises if the WD is overflowing its RL and the added mass to the NS triggers the QN. Due to the small separation, even higher WD temperatures may be reached, enabling oxygen burning and subsequently even nuclear statistical burning and the formation of iron-group elements. The caveat to this is that if the mass ratio $M_{\mathrm{WD}}/M_{\mathrm{NS}} < 2/3$, little mass is transferred—thus, the NS is less likely to undergo a QN during the mass transfer process since it may be too light to begin with.

In cases where the QN explosion does occur, it may be asymmetric, leading to a disruption of the binary and hence allowing the heavy element WD to survive as an isolated object. In summary, we predict the following.

1. The rate of formation of these exotic WDs should be related to LMXBs formation rate and should be more common in LMXB formation sites.
2. If the parent binary survived disruption (see Table 1), G87–7 should be in orbit around a QS. The QS X-ray luminosity is $L_{\mathrm{QS},X} \sim 2 \times 10^{36} \, \text{erg s}^{-1} \times P_{-11}^2$, where the QS period derivative $P$ is given in units of $10^{-11} \, \text{s}^{-1}$ (Ouyed et al. 2007).
3. For the heaviest WD ($M_{\mathrm{WD}} > 0.72 \, M_\odot$) experiencing the QN shock, degeneracy will not be lifted when carbon burning begins, and a sub-Chandrasekhar Type Ia SN may result in our model.

4. A CASE FOR GRB 110328A

GRB 110328A/Swift J164449.3 + 57345 (Cummings et al. 2011) has been localized to the core of a small galaxy in the constellation Draco at a redshift of $z = 0.35$ (Levan et al. 2011) and it has remained a strong, flaring X-ray source many days after the trigger, unlike known GRBs which do not exceed a few hours of activity. The energetics of the continuing event amount to an average luminosity in the X-rays of $L_X \sim 2.5 \times 10^{47} \, \text{erg s}^{-1}$ continuing for $\sim 10^4 \, \text{s}$ implying a total energy output of $E_{X,\mathrm{tot}} \sim 2.5 \times 10^{50} \, \text{erg}$ (Bloom et al. 2011a).

Assuming this energy is liberated in an accretion process at 10% efficiency, the total mass involved in accretion over the first day is $\sim 0.1 \, M_\odot$. This led to the suggestion that the event is related to tidal disruption of a $\sim 0.5 \, M_\odot$ main-sequence star by a massive BH (a few $\times 10^4 \, M_\odot$) residing in the core of the galaxy (e.g., Bloom et al. 2011b; Burrows et al. 2011). Here we offer an alternate explanation and argue that this event might be related to ablated WD material falling onto the QS. As shown next, our
model comes with specific predictions that can be tested against observations.

4.1. GRB 110328A in our Model

In our model, LMXBs with $M_{\text{WD}} < 0.43 M_\odot$ (i.e., an He WD) experiencing the QN when $a_{10} < a_{10}^{\text{max}}$ lead to ablation. The fate of the ablated material depends on many factors but here we consider a simplified picture. The velocity of the ablated WD material, which acquires momentum from the impacting QN ejecta, will consist of a combination of (1) orbital speed perpendicular to the line linking the explosion center to the WD, (2) impact velocity which is parallel to it along the radial direction, and (3) ejection velocity from ablation, $v_{\text{nuc.ejec.}}$ which is radial in the frame moving with the WD.

Momentum conservation $\beta_{\text{QN}} v_{\text{QN}} M_{\text{QS}}/G \times (R_{\text{WD}}/a_3^2) = M_{\text{WD, impact}} \sim 14.3 \text{ km s}^{-1} \times E_{\text{QN},52}/(a_3^2 M_{\text{WD},0.43}^5)$; (here $\beta_{\text{QN}} = 1$ is the usual relativistic parameter). The WD orbital speed is $\sim 2100 \text{ km s}^{-1} \times M_{\text{QS},1.8}/a_{10}^{\frac{1}{2}}$ so for the impact velocity to exceed the orbital speed the condition is

$$M_{\text{WD}} < 0.02 M_\odot \left(\frac{E_{\text{QN},52}}{a_3^2 M_{\text{QS},1.8}}\right)^{\frac{1}{5}} \left(\frac{9/10}{M_{\text{QS},1.8}}\right)^{\frac{3}{5}}$$

where $M_{\text{QS}}$ is the mass of the QS (hardly different than its progenitor heavy NS) in units of $1.8 M_\odot$. While there remains the possibility that the ejected/ablated material could be concentrated in a cone away from the explosion point, the above condition (note that $a_{10} < a_{10}^{\text{max}}$) suggests that in most cases the impact velocity can be neglected and only orbital and ejection/ablation speed play a dominant role. Thus, the ablated material will most likely be confined to a “fan” of spread-out (and expanding) WD ashes orbiting the QS.

The amount of material that will be trapped by the Bondi radius (material heading toward the QS) is $M_{\text{trap}} = \Omega_{\text{trap}} M_{\text{WD}}$, where the solid angle $\Omega_{\text{trap}} = R_B^2/4a_3^2$ with $R_B = 2GM_{\text{QS}}/v_{\text{nuc.ejec.}}^2 = 9.9 \times 10^5 \text{ cm} \times M_{\text{QS},1.8}/a_{10}^{\frac{1}{2}}$ being the Bondi radius (Bondi & Hoyle, 1944). So the amount of material trapped by the QS is

$$M_{\text{trap}} = 0.25 M_{\text{WD}} \times M_{\text{QS},1.8}^2 \left(\frac{1}{10} \frac{M_{\text{Q}}}{a_{10}^{\frac{1}{2}}} \frac{a_{10}^3}{M_{\text{Q}}^2}ight),$$

i.e., at least 1/4th of the WD mass will fall onto the QS.

Bondi accretion rate is $m_B = 4\pi \rho_{\text{abl}} G^2 M_{\text{QS}}^2 / v_{\text{nuc.ejec.}} \simeq 10^{-3} M_{\odot} \text{ s}^{-1} \times M_{\text{WD}} / 0.25 M_{\text{Q},1.8}^2 / (a_{10}^{1/2} A_{10}^{3/2})$, where $\rho_{\text{abl}} = M_{\text{WD}} / (4\pi/3 a_3^3)$ is the density of the falling ashes of the ablated WD. As shown in Romanova et al. (2003), only a fraction of the Bondi flux will accrete onto a magnetized, rotating compact WD. As already argued in OSJ, our model suggest that the GRB engine for some short GRBs resides in globular clusters (GCs) where many LMXBs are seemingly found (Bogdanov et al. 2006; Camilo & Rasio 2005). Thus, events such as GRB 110328 A and $\alpha$-elements WDs in our models will most likely reside in GCs and as such we expect them to be astrometrically coincident with halos and nuclei of galaxies.

We have discussed how a QN may be able to restart fusion processes in a WD that happens to be in a close binary with the exploding NS, which could explain the occurrence of heavy elements in WDs. We found that WD more massive than $0.43 M_\odot$ can burn carbon without being ablated. One may wonder if a QN is really necessary, or if a Type Ia SN occurring with a WD orbiting it could produce similar events? However, the kinetic energy of the SN ejecta in a Type Ia SN is thought to be about $10^{51} \text{ erg}$ (rather than $10^{52} \text{ erg}$ as in the case of a QN), making it unlikely that the temperature will be high enough to start nuclear processes. Finally, we note that in the cases when

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8 Animation online at http://quarknova.ucalgary.ca/media/

9 A bare QS has strong electric fields at the surface, which provides additional repulsion to any positively charged species (Page & Usov 2002; Cheng & Harko 2003). Magnetic field on the surface of a QS do not change the scenario (Jaikumar 2006).
the WD is not heated to temperatures that allow for nuclear burning, it may still get very hot. This therefore opens up the possibility of a very old and hot WD.

To summarize: if a QN occurs in a close binary with a WD, then the QN may trigger nuclear burning in the WD. If the WD is an He WD or a very low mass CO WD ($M_\odot < 0.43$), then the WD will get completely ablated and a GRB 110328A phenomena may result. If the CO WD has a higher mass it may survive the QN, and the nuclear processes will lead to the formation of a heavy element WD. Detailed hydrodynamical and nucleosynthesis calculations are ultimately required to test our assumption that the WD can, under certain conditions, avoid the thermonuclear runaway associated with Type Ia SN explosions.

The research of R.O. is supported by an operating grant from the National Science and Engineering Research Council of Canada (NSERC). P.J. acknowledges start-up funds from California State University Long Beach. This work has been supported, in part, by grant AST-0708551 from the U.S. National Science Foundation and, in part, by grant NNX10AC72G from NASA’s ATP program.

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