Quark-Noave in binaries:
Observational signatures and implications to astrophysics

Rachid Ouyed*, Denis Leahy, Nico Koning
Department of Physics and Astronomy, University of Calgary,
834 Campus Place N.W., Calgary, AB, Canada, T2N 1N4
*E-mail: rouyed@ucalgary.ca

Jan E. Staff
Department of Astronomy, University of Florida,
P.O. Box 112055, Gainesville, FL, 32611-2055, USA

The explosive transition of a massive neutron star to a quark star (the Quark-Nova; QN) releases in excess of $\sim 10^{52}$ erg in kinetic energy which can drastically impact the surrounding environment of the QN. A QN is triggered when a neutron star gains enough mass to reach the critical value for quark deconfinement to happen in the core. In binaries, a neutron star has access to mass reservoirs (e.g. accretion from a companion or from a Common Envelope; CE). We explain observed light-curves of hydrogen-poor superluminous Supernovae (SLSNe Ia) in the context of a QN occurring in the second CE phase of a massive binary. In particular this model gives good fits to light-curves of SLSNe with double-humped light-curves. Our model suggests the QN as a mechanism for CE ejection and that they be taken into account during binary evolution. In a short period binary with a white dwarf companion, the neutron star can quickly grow in mass and experience a QN event. Part of the QN ejecta collides with the white dwarf; shocking, compressing; and heating it to driving a thermonuclear run-away producing a SN Ia impostor (a QN-Ia). Unlike “normal” Type Ia supernovae where no compact remnant is formed, a QN-Ia produces a quark star undergoing rapid spin-down providing additional power along with the $^{56}$Ni decay energy. Type Ia SNe are used as standard candles and contamination of this data by QNe-Ia can infer an incorrect cosmology.

Keywords: stars: evolution, supernovae: general, stars: neutron, stars: white dwarfs

1. Introduction

A QN is the explosive transition of a massive neutron star (NS) to a quark star (QS; the compact remnant). It ejects the outermost layers of the NS as the relativistic QN ejecta with kinetic energy exceeding $10^{52}$ erg. The interaction of this ejecta with its surroundings leads to unique phenomena and has important implications to astrophysics. When occurring in binaries, Quark-Novae (QNe) have the potential to transform our view of binary evolution and has serious implications to both high-energy astrophysics and cosmology. After a description of the QN and its energetics in section 2, we briefly review two cases of QNe in binaries. The first case is a QN-Ia (section 3) which is a QN going off in a short period binary consisting of (the exploding) NS and a white dwarf (WD) which is the mass reservoir. The extremely dense relativistic QN ejecta impacts (shocks, compresses and heats) the WD and triggers the thermonuclear run-away of a traditional Type Ia. Along side the type Ia, the spinning-down QS provides an additional power source which “tampers” with the energy budget. In the second case, we show that a QN occurring in a
massive binary can account for the "exotic" light-curves of double-humped hydrogen poor SLSNe (section 4). We summarize in section 5.

2. Quark Nova : Overview, energetics and dynamics

We define $M_{NS,c}$ as the critical mass for a non-rotating NS to undergo quark deconfinement in its core. The presence of enough strange quarks in the deconfined core of the NS then triggers the conversion of hadrons (i.e. matter made of up and down quarks) to the conjectured more stable $\text{(uds)}$ matter (i.e. matter made of free up, down and strange quarks).\textsuperscript{1,2} In a QN\textsuperscript{3}, the $(ud)$-to-$(uds)$ conversion front propagates toward the surface of the NS while harnessing neutrino\textsuperscript{4}, photon\textsuperscript{5} and gravitational energy\textsuperscript{6,7} possibly yielding a detonative regime. Micro-physics driven hydrodynamical simulations of this conversion process seem to indicate that a detonation may indeed occur\textsuperscript{6} and when coupled with gravitational collapse may lead to a universal mechanism for the ejection of the NS outermost layers ($M_{QN} \sim 10^{-3} M_\odot$ of QN ejecta) with a universal kinetic energy, $E_{QN,KE}$, of a few times $10^{52}$ erg (i.e. with an associated Lorentz factor exceeding $\Gamma_{QN} \sim 10$)\textsuperscript{6,8}. Thus the kinetic energy released in a QN exceeds that of a supernova by at least an order of magnitude.

The neutron-rich QN ejecta provides a favorable site for r-process nucleosynthesis\textsuperscript{9,10}. When this ejecta (expanding radially outward from the parent NS) collides with the preceding SN ejecta, it re-energizes and re-brightens the SN yielding a superluminous SN\textsuperscript{11}. This double-detonation generates a superluminous double-peaked light-curve if the time-delay between the SN and the QN exceeds a few days. We account for the luminosity\textsuperscript{12}, the photometric/spectroscopic signatures\textsuperscript{13} as well as introduce nuclear/spallation signatures resulting from the interaction of the ultra-relativistic QN ejecta with the SN shell and circumstellar material\textsuperscript{14}. For shorter time-delays of less than a day, the QN kinetic energy is lost to PdV work but the collision between the r-process-rich QN ejecta with the SN ejecta yields unique nuclear signatures which may explain existing observations\textsuperscript{15}. The QS shows features reminiscent of soft gamma repeaters\textsuperscript{16} while the explosion energetics and variability are reminiscent of gamma-ray bursts\textsuperscript{17}.

When occurring in binaries, the more complex interactions with the companion result in even more interesting features. We review the key signatures and main implications to astrophysics in this paper.

3. Quark Nova Ia : A QN in a low-mass X-ray binary

We first discuss what happens when a NS in a close binary with a WD companion explodes as a QN. In this scenario, Roche-Lobe overflow disrupts the WD which produces a Carbon-Oxygen (CO) torus surrounding the NS\textsuperscript{19,20}. Alternatively, the NS may fully merge with the WD so that the NS now is in the core of the WD when the QN occurs. The QN will be triggered following sufficient mass accretion.

Some of the relativistic QN ejecta will impact (shock, heat and compress) the disrupted WD inducing a runaway nuclear burning of the CO in an event we termed
a QN-Ia since it is “Type Ia”-like explosion. A crucial difference here however is the QS which provides extra power through magnetic braking spin-down and consequently a QN-Ia (which spectrum resembles a Type-Ia SN) is powered by a combination of $^{56}$Ni decay and the spin-down luminosity of the QS. This has drastic consequences for cosmological models if QNe-Ia contaminate the sample of Type Ia SNe used as distance indicators in cosmology as discussed below.

### 3.1. Implication for cosmology

The spin-down contribution yields a red-shift-dependent Phillips-like relation \((20)\) Figure 1 shows the correlation between peak absolute magnitude and light-curve shape) which means that they can confuse (i.e. are NOT rejected by the) light-curve fitters used for cosmology \((20)\) Figure 4). The rate of QNe-Ia may be a significant fraction of the observed Type Ia SNe and may be dominant at higher redshift\((20)\). This is especially egregious given that the QN-Ia light-curve varies with redshift.

To estimate the effect of contamination, we analyzed hundreds of synthetic QNe-Ia light-curves using the SALT2 light-curve fitting software \((21)\) to find the difference \(\Delta \mu(z)\) between the actual distance modulus and the fitted distance modulus as a function of redshift, \(z\). Most of the simulated QNe-Ia were best fitted with:

\[
\Delta \mu(z) = -1.13655 e^{-0.39035z} + 1.32865 .
\]

For \(z = 0\) there is a strong correlation since \(\Delta \mu(z) \approx 0\), but at \(z = 1.5\) the correlation is much weaker \(\Delta \mu \approx 0.7\). We conclude that if QNe-Ia represent an important fraction of the SNe used in the work which estimates the accelerating expansion of the Universe, this may have drastically altered the statistics and conclusions of those studies\((20)\). It is thus vital to differentiate between QNe-Ia and standard SNe-Ia. Applying our correction above to the Union2.1 data\((24)\) we obtain the true distance moduli of the observed SNe-Ia (if they are indeed QNe-Ia) as shown by red crosses in\((20)\) Figure 6. This demonstrates how the SNe-Ia distance moduli, when corrected, lay very close to the \(\Omega_M = 1, \Omega_\Lambda = 0\) curve.

A QN-Ia may have already been observed in SN 2014J\((25)\). SN 2014J’s $^{56}$Ni mass was estimated to be \(\sim 0.36 M_\odot\)\((26)\) based on $^{56}$Co decay lines. However, based on the peak luminosity, \(M_{Ni} \sim 0.77 M_\odot\) is expected. In the QN-Ia model, the discrepancy can be accounted for by the QS spin-down power. Perhaps the best prospect for observationally distinguishing a QN-Ia from a SN-Ia is the detection of the gravitational wave signal produced during the explosive transition of the NS to a QS. If the QN is asymmetric, it should emit a gravitational wave signal that could be observable by Advanced LIGO\((27)\). This would be followed by another signal from the exploding WD: here the time delay between the QN and the exploding WD is the time it takes the QN ejecta to reach the disrupted WD plus the burning time of the WD. Other types of Type Ia SNe (i.e. single or double degenerate scenarios) would lack such a dual signal. Another strong observational signature of a QN-Ia is high-energy emission (specifically X-ray signatures\((16,17)\)) from the QS which would
4. Quark Novae in Massive Binaries: a model for SLSNe Ia

QNe are likely to occur in binaries experiencing CE phases where the NS can accrete enough mass to reach $M_{NS,c}$. In particular, in massive binaries experiencing two CE phases, the NS would have access to two mass reservoirs\cite{29,30}. In this picture, the NS would have evolved earlier from its more massive progenitor and is companion to the second star during its CE phase.

When the system enters the CE phase (in which the hydrogen envelope is ejected), it leaves behind a close binary consisting of the NS and the giant star’s He core. At this point the He-core has a mass of a few $M_\odot$ and an orbital separation of $\sim 3 \, R_\odot$\cite{29} (Figure 1). During this phase, the NS accretes up to $\sim 0.1 \, M_\odot$ and relies on the second CE to grow in mass. The He core then expands causing a second He-rich CE phase. Sufficient mass is accreted onto the NS during this second CE and the NS reaches $M_{NS,c}$ and undergoes a QN explosion inside the expanded Hydrogen-poor envelope. The QN ejecta shocks and unbinds the CE providing a bright, short-lived hump matching those observed in double-humped SLSNe\cite{29,30}.

Following the QN, the remaining system consists of a QS and the CO core (of mass $M_{CO}$) of the He star. Orbital decay lead to a merger a few days to a few weeks following the QN event. The QS then rapidly accretes from the CO core leading to the collapse of the QS into a Black Hole (BH). The remainder of the CO core is subsequently accreted by the BH. The accretion luminosity powers the long lasting main hump of the double-humped SLSN. Figure 1 shows our fit to the recently discovered SLSN ASASSN-15lh\cite{31}. We fit it with a CE mass and radius
of $5M_\odot$, 3000$R_\odot$, respectively. The BH-accretion parameters are $2 \times 10^{46}$ erg s$^{-1}$ for the initial accretion luminosity with an injection power in time $\propto t^{-1.5}$. The time delay between the QN event and the onset of BH-accretion is 20 days. These parameters are similar to those we used to fit a number of hydrogen-poor SLSNe [30] (Table 2 and Figure 2). Our model can also fit double-peaked SLSNe showing late-time emission (e.g. iPTF13ehc and LSQ14bdq) which we modelled as the collision between the He-rich CE (ejected by the QN) and the hydrogen-rich (i.e. first) CE ejected during the first CE phase [30] Figure 1). The available accretion energy $\eta_{BH}M_{CO}c^2$ ($\eta_{BH}$ is the BH-accretion efficiency) is enough to account for the extreme radiation released during the long-lasting hump in SLSNe. The QN is key to our model since besides accounting for the first peak, it also ejects the second CE at speeds of a few 10,000 km s$^{-1}$ which ensures a very efficient harnessing of the BH-accretion input power by the very large envelope a few days to a few weeks following the QN event. The QN deposits its momentum and energy impulsively in the CE which makes our model fundamentally different from those involving spin-down power where the energy is deposited gradually.

5. Summary

QNe should be common in binaries where accretion onto the NS from a companion (i.e. the disrupted WD in LMXBs) or during a CE phase (i.e. during massive binaries evolution) can drive the NS above the critical mass, $M_{NS,c}$, triggering the QN. The ability of the QN model in binaries to fit SLSNe in general (see http://www.quarknova.ca/LCGallery.html) and in particular a number of double-peaked SLSNe Ia, suggests that QNe may be an important component of massive binary evolution and may even be responsible for CE ejection. The QN-Ia model has two main interesting features: First, the detonation of the WD in the QN-Ia scenario is explained by standard shock physics governing the interaction of the QN ejecta and the WD. Secondly, the QN-Ia provides an elegant explanation for the correlation between peak magnitude and light-curve shape through the contribution of spin-down energy to the light-curve. Our model can be tested by further work including simulations of QNe in binary evolution. Our model relies on the feasibility of the QN explosion which requires sophisticated simulations of the burning of a NS to a QS which are being pursued. Preliminary simulations with consistent treatment of nuclear and neutrino reactions, particle diffusion and hydrodynamics show instabilities which could lead to a detonation [32]. We also propose that a “core-collapse” QN could result from the collapse of the quark matter core [33] which provides another avenue for the explosion.

Acknowledgments

The research of RO, DL and NK is funded by the Natural Sciences and Engineering Research Council of Canada. J.E.S is funded by the University of Florida Theoretical Astrophysics Fellowship.
References

1. A. R. Bodmer, *PhRvD*, 4, 1601, (1971)
2. E. Witten, *PhRvD*, 30, 272, (1984)
3. R. Ouyed, J. Dey and M. Dey, *A&A*, 390, 39, (2002)
4. P. Keränen, R., Ouyed and P. Jaikumar, *ApJ*, 618, 485 (2005)
5. C. Vogt, R., Rapp and R. Ouyed, *Nuclear Physics A*, 735, 543 (2004)
6. B. Niebergal, R. Ouyed and P. Jaikumar, *PhRvC*, 82, 062801 (2010)
7. R. Ouyed, B. Niebergal and P. Jaikumar, “Explosive Combustion of a Neutron Star into a Quark Star: the non-premixed scenario” in proceedings of Compact Stars in the QCD phase diagram (CSQCDIII), Eds. L. Paulucci, J. E. Horvath, M. Chiapparini, and R. Negreiros, http://www.slac.stanford.edu/econf/C121212/ [arXiv:1304.8048] (2013)
8. R. Ouyed, and D. Leahy, *ApJ*, 696, 562 (2009)
9. P. Jaikumar, B. Meyer, B. S. Otsuki, and R. Ouyed, *A&A*, 471, 227 (2007)
10. M. Kostka, N. Koning, Z. Shand, et al., *A&A*, 568, A97 (2014)
11. D. Leahy and R. Ouyed, *MNRAS*, 387, 1193, (2008)
12. R. Ouyed, M. Kostka, N. Koning, et al. 2012, *MNRAS*, 423, 1652 (2012)
13. M. Kostka, N., Koning, D. Leahy, et al., *RevMexAstron.Astrop.*, 50, 167 (2014)
14. R. Ouyed, D., Leahy, A., Ouyed and P. Jaikumar, *PhRvLett.*, 107, 151103 (2011)
15. R. Ouyed, D. Leahy and N. Koning, *RAA*, 15, 483 (2015)
16. R. Ouyed, D. Leahy and B. Niebergal, *A&A* 473, 357, (2007a)
17. R. Ouyed, D. Leahy and B. Niebergal, *A&A* 475, 63, (2007b)
18. J. E. Staff, R. Ouyed and M. Bagchi, M. 2007, *ApJ*, 667, 340 (2007)
19. R. Ouyed and J. E. Staff, *RAA*, 13, 435, (2013)
20. R. Ouyed, N. Koning, D. Leahy, et al., *RAA*, 14, 497, (2014)
21. J. Guy et al., *A&A*, 466, 11, (2007)
22. S. Perlmutter, et al. *ApJ*, 517, 565, (1999)
23. A. G. Riess, et al., *AJ*, 116, 1009, (1998)
24. N. Suzuki, D., Rubin, C., Lidman, et al. *ApJ*, 746, 85 (2012)
25. R. Ouyed, D. Leahy, N. Koning and J. E. Staff, *ApJ*, 801, 64, (2015)
26. E. Churazov et al., *Nature*, 512, 406, (2014)
27. J. E. Staff, P. Jaikumar, V. Chan and R. Ouyed, *ApJ*, bf 751, 24, (2012)
28. R. Ouyed, B. Niebergal, W. Dobler and D. Leahy, *ApJ*, 653 558 (2006)
29. R. Ouyed, D. Leahy and N. Koning, *MNRAS*, 454, 2353, (2015)
30. R. Ouyed, D. Leahy and N. Koning, *ApJ*, in press (2016), http://arxiv.org/abs/1510.06135
31. S. Dong, B. J. Shappee, J. L. Prieto, et al. Science Magazine, 351, issue 6270, 257 (2016)