Predictions for signatures of the quark-nova in superluminous supernovae

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Abstract

Superluminous Supernovae (more than a 100 times brighter than a typical supernova (SN); e.g. SN2006gy, SN2005gj, SN2005ap, SN2008fz, SN2003ma) have been a challenge to explain by standard models. For example, pair instability SNe which are luminous enough seem to have too slow a rise, and core collapse SNe do not seem to be luminous enough. We present an alternative scenario involving a quark-nova (QN), an explosive transition of the newly born neutron star to a quark star in which a second explosion (delayed) occurs inside the already expanding ejecta of a normal SN. The reheated SN ejecta can radiate at higher levels for longer periods of time primarily due to reduced adiabatic expansion losses, unlike the standard SN case. Our model is successfully applied to SN2006gy, SN2005gj, SN2005ap, SN2008fz, SN2003ma with encouraging fits to the lightcurves. There are four predictions in our model: (i) superluminous SNe optical lightcurves should show a double-hump with the SN hump at weaker magnitudes occurring days to weeks before the QN; (ii) Two shock breakouts should be observed vis-a-vis one for a normal SN. Depending on the time delay, this would manifest as two distinct spikes in the X-ray region or a broadening of the first spike for extremely short delays; (iii) The QN deposits heavy elements of mass number $A > 130$ at the base of the preceeding SN ejecta. These QN r-processed elements should be clearly visible in the late spectrum (few days-weeks in case of strong ejecta mixing) of the superluminous SN and should be absent in the late spectrum of normal (single explosion) SNe; (iv) The QN yield will also contain lighter elements (Hydrogen and Helium). We expect the late spectra to include H_α emission lines that should be distinct in their velocity signature from standard H_α emission usually attributed to preshocked circumstellar material.

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1 Introduction

At high baryon density and vanishing pressure, the ground state of bulk matter may not be iron (^{56}Fe), but deconfined strange quark matter (SQM) made up of up, down, and strange (u, d, s) quarks (e.g. Bodmer 1971, Witten 1984)[1]. In that case, once the density for a transition to the (u, d, s) phase is reached in the core of a neutron star, it is likely that the entire star is contaminated and converted into a (u, d, s) star (e.g. Haensel et al. 1986; Alcock et al. 1986). However, the SQM hypothesis faces skepticism for lack of direct evidence of its existence and theoretical uncertainty regarding the threshold density (see Appendix A for a discussion on SQM and the disaster scenario).

In 2000, researchers at CERN evaluated results from seven separate experiments (involving collisions between large nuclei) to show that a state of matter in which quarks were not confined had been created (e.g. Margetis et al. 2000). Experiments at the relativistic heavy-ion collider (RHIC) at Brookhaven National Laboratory have since conclusively discovered a liquid-like state of deconfined but interacting quarks and gluons termed the Quark-Gluon Plasma (sQGP) at high temperature (eg. Nagle & Müller 2006). Certain features of these experiments prove beyond doubt that for a short instant one has created, and in fact significantly exceeded, the conditions required for quark deconfinement. This result, along with the theoretical advance in color superconductivity in cold and dense matter (eg. Rapp et al. 1998; Alford et al. 1998; Alford et al. 1999) revived the topic of SQM and formation mechanisms of quark stars and opened doors for the exploration of the post-neutron-star-pre-black-hole stage in the evolution of compact stars.

Ouyed, Dey, & Dey (2002; hereafter ODD) considered the intriguing possibility that the transition from a neutron star to a quark star might in fact be an explosive one and involves two steps in a scenario called the Quark-Nova (QN). First, the neutron star core converts to (u,d) matter. Then, as shown in Keränen, Ouyed, & Jaikumar (2005; hereafter KOJ), the dense (u, d) core collapses to the corresponding stable, more compact (u, d, s) configuration faster than the overlying material

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[1]Introducing strange quarks into matter costs energy because the strange quark mass is heavier than that of the up and down quarks. That is why the Λ^0 baryon (also made up of an u-quark, a d-quark, and an s-quark) in vacuum is heavier than the neutron/proton. It decays to them via weak interactions. But as the baryon density is increased, up and down quarks Fermi levels go higher and higher. One needs 2 d-quarks for every u-quark to maintain neutrality. At some point, this becomes more expensive than introducing the s-quark because the mass of the s-quark is compensated by the fact that one needs only 1up, 1 down and 1 s-quark to make a zero charge unit. So the Fermi level of the d-quark comes down (in other words, the d-quark will decay to an s-quark as density becomes higher and higher). Eventually, we end up with SQM at high density. In general weak decays are prevented in bulk degenerate matter by filled Fermi sea. E.g., the neutron is unstable in vacuum but relatively more stable in a neutron star (the direct urca does occur but the lifetime of neutron is much longer).

(neutron-rich hadronic envelope) can respond. In other words, the growing quark core collapses before it engulfs the overlaying layers of the parent neutron star. While this proposition of an explosive transition awaits more detailed theoretical and numerical investigations in order to be confirmed with certitude, it nevertheless found many interesting applications in high energy astrophysics phenomena such as Gamma-ray Bursters (Staff, Ouyed, & Bagchi 2007; Staff, Niebergal, & Ouyed 2008), Ultra-High Energy Cosmic Rays (Ouyed, Keränen, & Maalampi 2005), Re-ionization (Ouyed, Pudritz, & Jaikumar 2009), and Cooling of magnetars (Niebergal et al. 2009). These studies hint to the idea that QNe do go off in the universe.

In the QN model, core deconfinement to (u,d) might occur during or after a SN explosion, so long as the central density of the protoneutron star is high enough to induce phase conversion. Theoretical and numerical work is underway on describing the details of the conversion of ordinary nuclear matter to quark matter inside neutron stars, in an attempt at improving initial efforts (eg. Olinto 1987; Drago et al. 2007). This is intimately connected to recent advances in our understanding of the equation of state of high-density matter and color superconductivity. Needless to say, the propagation of the burning front associated with this phase transition is crucial in determining the energetics of the explosion and ejecta dynamics.

Staff, Ouyed & Jaikumar (2006), using state-of-the-art simulations showed that massive neutron stars ($\sim 1.5 M_\odot$) born with core densities a few times nuclear density and spinning at millisecond periods are most likely to reach the quark deconfinement density quickly. These heavy neutron stars (with progenitor mass $> 25 M_\odot$) would experience a QN episode generating a second explosion following the first (i.e. the SN). The delay between the first explosion and the second one varies from a few seconds to a few years depending on the birth parameters (mass, period and magnetic field) of the parent neutron star (see Staff, Ouyed, & Jaikumar 2006). Here we describe the application of such a delay for superluminous SNe and briefly discuss the general implication to high energy astrophysics.

This proceedings note is organized as follows. In section 2, we describe the essential mechanism and features of the QN. In section 3, we describe in detail the efficacy of the dual-shock QN model in describing the outstanding features of a host of superluminous SNe, with emphasis on the successful interpretation of photometric and spectroscopic results. Section 4 contains an overview of QN dynamics, in particular, the explosive photon fireball that opens up the connection to high-energy astrophysical phenomena as well as r-process nucleosynthesis of the heavy elements in a unified way.

2 The Quark-nova

The QN model describes the birth of a quark star (see Appendix A on the question of co-existence of neutron stars and quark stars). In the QN model, the *(u,d)* core of a hybrid star[2], that undergoes the phase transition to the *(u,d,s)* quark phase, shrinks in a spherically symmetric fashion to a stable, more compact strange matter configuration faster than the overlaying material (the neutron-rich hadronic envelope) can respond, leading to an effective core collapse. The core of the neutron star is a few kilometers in radius initially, but shrinks to 1-2 km in a collapse time of about 0.1 ms (Lugones et al. 1994). The gravitational potential energy released during this event is converted partly into internal energy (latent heat) and partly into outward propagating shock waves which impart kinetic energy to the material that eventually forms the QN ejecta.

There are three previously proposed mechanisms for ejection of the outer layers of the neutron star (i.e. crust): (i) Unstable baryon to quark combustion leading to a shock-driven ejection (Horvath & Benvenuto 1988). More recent work, assuming realistic quark matter equations of state, argues for strong deflagration (Drago et al. 2007) that can expel surface material. In these models up to $10^{-2}M_\odot$ can be ejected. These calculations focus on the microphysics and not on the effect of the global state of the resulting quark core which collapses prior to complete combustion (KOJ), leading to conversion only of the inner core ($\sim$ 1-2 km) of the neutron star; (ii) Neutrino-driven explosion where the energy is deposited in a thin (the densest) layer at the bottom of the crust above a gap separating it from the collapsing core (KOJ). For the neutrino-driven mechanism, the core bounce was neglected, and neutrinos emitted from the conversion to strange matter transported the energy into the outer regions of the star, leading to heating and subsequent mass ejection. Consequently, mass ejection is limited to about $10^{-5}M_\odot$ (corresponding to the crust mass below neutron drip density) for compact quark cores of size (1-2) km; (iii) Thermal fireball driven ejection which we consider for the present study. The fireball is inherent to the properties of the quark star at birth. The birth temperature was found to be of the order of 10-20 MeV since the collapse is adiabatic rather than isothermal (Ouyed, Dey, & Dey 2002; KOJ). In this temperature regime, we assume the quark matter is in one of the possible superconducting phases, called the Color-Flavor Locked (CFL; see Appendix B for an extended definition) phase (Rajagopal&Wilczek 2001) where the photon emissivity dwarfs the neutrino emissivity (Jaikumar, Rapp, & Zahed 2002;

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[2]As outlined in KOJ, the initial state for the QN is that of a deleptonized neutron star with a *(u,d)* core. In the QN, the two-step process, neutron to *(u,d)*, then *(u,d)* to *(u,d,s)* is crucial. In our case, the neutrinos come from weak reactions at the edge of the *(u,d)* core and can leak out easily into the surrounding cooler and deleptonized envelope where they can deposit energy. This is significantly different from phase conversion in a proto-neutron star stage where neutrino transport is slower (of the order of seconds) because of the hot and lepton-rich matter.

Vogt, Rapp, & Ouyed 2004; Ouyed, Rapp, & Vogt 2005). This is because the critical temperature of the CFL phase is high $T_c \sim 50$ MeV, so that even at temperatures of tens of MeV, there is a large amount of thermal energy in the CFL photons due to in-medium effects. We discuss the photon fireball mechanism in detail in Section 4.1.

2.1 Dual-shock Quark-Novae

Before the QN has occurred, one has the progenitor collapse (the SN proper). The conversion from NS to QS depends on the NS central density at birth. Progenitors with mass $> 25M_\odot$ would lead to a neutron star heavy enough ($\sim 1.5M_\odot$) to experience the transition. For low angular momentum progenitors, the combination of a high neutron star core density at birth and, most likely, fall-back material would drive the proto-neutron star to a black hole. High angular momentum progenitors (collapsars), will delay the formation of a black hole for three main reasons: (a) the progenitor's core tends to shed more mass and angular momentum as it shrinks reducing central core mass and fall-back; (b) high spin keeps the core density of the resulting neutron star from crossing the black hole formation limit; (c) high angular momentum in the material around the core reduces the accretion rate onto the central object. All together, collapsars seem to provide favorable conditions for the QN to occur inside them. We take the stellar structure of a Helium Wolf-Rayet star (e.g. Meynet & Maeder 2003; Heger et al. 2003; Petrovic et al. 2006) to be representative of the progenitor and consider the low and high-metallicity cases. The main difference is that the high metallicity star would have an extended envelope. For example, for a $30M_\odot$ star a rough estimate yields $\sim$ 3-5$R_\odot$ while in the low metallicity case, the star envelope cuts off sharply at $\sim$ 1.5-2.5$R_\odot$.

When the iron-rich broken pieces of QN ejecta (see Ouyed&Leahy 2009) impact this stellar envelope (the already expanding SN ejecta), they undergo a shock and become heated. Let us define a certain time delay, $t_{\rm delay}$, as the time elapsed between the SN and the QN explosion. For delays we are concerned with here the SN density is high enough that the QN ejecta is vaporized at impact, effectively depositing their kinetic energy at the base of the SN envelope. The details of this interaction can be found in §2 in Ouyed et al. (2009). The resulting QN shock propagating at speed $v_{\rm QN}$ reaches the outer edge of the SN ejecta (becomes visible to the observer) at distance $R_{\rm QN}$ and at time $t_{\rm delay} + t_{\rm prop.}$ where $t_{\rm prop.} = R_{\rm QN}/v_{\rm QN}$ is the propagation time delay for the QN shock to reach the edge of the SN ejecta; *which defines the shock breakout in our model which, of course, occurs after the SN breakout shock.* As we show in the next section this interaction between the QN and SN ejecta leads to lightcurves and durations observed in superluminous SNe.

3 Superluminous SNe

3.1 Models for light curves

SN2006gy was discovered on 18 September 2006 by Robert Quimby. It is a Type IIn SN characterized by the bright peak magnitude $M_R \sim -22$ mag and its long duration (more than 100 times brighter and significantly longer-lasting than a typical SN). The fundamental question is how is it possible to power the observed lightcurve ($> 10^{51}$ erg in radiation) for so long (hundreds of days).

Ofek et al. (2007) argued that the extreme luminosity could have been produced by collision between a Type Ia SN's ejecta and circumstellar material (CSM). But Smith et al. (2007) point out that in the SN2006gy case one requires an implausibly massive envelope and that no Type Ia features were seen. Smith et al. (2007) instead argue for a pair instability SN (PISN) model with 22 $M_\odot$ of Ni^{56} to account for the peak luminosity. This is orders of magnitudes more than what is produced in an ordinary core-collapse SN, and would occur only for the most massive stars ($> 150 M_\odot$)[3]. Even if such progenitors can occur in the local universe, PISN models rise extremely slowly compared to SN2006gy (e.g. Figure 6 in Kawabata et al. 2009). Most recently, Kawabata et al. (2009) performed optical spectroscopy and photometry of SN 2006gy at late time, 400 days after the explosion. The fits to the lightcurve (see the right panel in their Figure 6) again requires extremes values with kinetic energy of about 6.4×10^{52} ergs, ejected envelope mass of about $53 M_\odot$, and total mass in Nickel of about 15 $M_\odot$.

In this context, the QN model provides a natural explanation. The crucial implications and observational consequences of the QN model are: **1)** In a QN, the energy input is delayed from the original core collapse explosion, allowing for re-energization of the SN ejecta at larger radius. A typical QN releases up to $\sim 10^{53}$ erg in kinetic energy (Ouyed, Rapp & Vogt 2005 and references therein). The QN ejecta is expelled at ultra-relativistic speeds (Ouyed& Leahy 2008) and re-energizes the preceding SN ejecta as it catches up and collides with it (Ouyed et al. 2009); and **2)** the resultant shock wave causes the outer layers of the neutron star to decompress, releasing free neutrons and neutron-rich seed nuclei from the crust that can capture these neutrons to form heavy elements via the r-process (Jaikumar et al. 2007).

When Leahy & Ouyed applied the QN model to SN2006gy (with a delay of $t_{\text{delay}} = 15$ days between the SN and the QN), it gave an excellent fit (see Figure 1 attached; from Leahy & Ouyed 2008). They also applied the QN model to two other superluminous SNe: SN2005ap (Quimby et al. 2007) and SN2005gj (Aldering

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[3]Heger & Woosley (2003) advanced the idea of a pulsational pair-formation SN and argued that the interaction of successive ejection (separated by a few years) would lead to the extreme luminosity. This would require extreme mass-loss rates (a fraction of a solar mass per year) for such a scenario and it is not clear why such an instability will be limited to only two ejections.

et al. 2006). As can be seen from the right panel in Figure 1, the QN model gives a good fit with the delay between the SN and QN as the only parameter ($t_{\mathrm{delay}} = 40$ days for SN2005ap and $t_{\mathrm{delay}} = 10$ days for SN2005gj). Here we revisit the dual-shock QN in the context of superluminous SNe applying it to more candidates. We make specific predictions as described below.

3.2 Photometry: *The double-hump*

The Leahy & Ouyed (2008) model is based on additional energy input into the SN ejecta: (i) The explosion occurs inside an extended expanding envelope; (ii) The delay is due to conversion of neutron star (NS) to a quark star (QS). We emphasize the crucial role of the second explosion due to this delayed conversion. Benvenuto& Horvath (1989) explored the idea of conversion energy release to power SN1987A, which is a regular SNe. However, they do not calculate any lightcurves or consider explosive conversion making use of the conversion delay. As shown in Leahy & Ouyed (2008) this allows for more luminous and long-lasting explosion since much of the radiation is emitted rather than being lost to adiabatic expansion. The time-dependent luminosity of a dual-shock QN is given by

$$L_{\mathrm{SN}}(t) = c_{\mathrm{v}} \Delta T_{\mathrm{core}} n_{\mathrm{ejec.}} 4\pi R_{\mathrm{phot.}}(t)^2 \frac{dD(t)}{dt} \ , \tag{1}$$

where $c_{\mathrm{v}} \sim (3/2)k_{\mathrm{B}}$ is the specific heat of the ejecta, $\Delta T_{\mathrm{core}} \sim T_{\mathrm{core}} = T_{\mathrm{QN,0}} R_0^2/(R_0 + v_{\mathrm{SN}}t)^2)$ is the core temperature of the ejecta; R_0 is the radius of the progenitor, v_{SN} the speed of the SN ejecta, and $T_{\mathrm{QN,0}}$ is the temperature of the SN ejecta when it is first reheated by the QN shock. Also, n_{ejec} is the number density of the ejecta, $R_{\mathrm{phot.}}(t)$ is the photospheric radius and $D(t)$ is the photon diffusion length (see Leahy&Ouyed 2008 for mode details). The resulting light curve is a superposition of light curves from different parts of the reshocked SN shell, with different rise times, different peaks, and different shapes. The corresponding light curve in the case of SN2006gy is shown in Figure 1 (solid and dash-dot lines for R- and V-band, respectively) and corresponds to an SN explosion at $t = 0$ with ejecta mass $M_{\mathrm{ejec.}} = 60M_\odot$, $R_0 = 10R_\odot$, $t_{\mathrm{delay}} = 15$ days, $v_{\mathrm{QN}} = 6000$ km s^{-1}, and $T_{\mathrm{QN,0}} = 0.4$ MeV. The lightcurve was computed by averaging over 13 equal solid angle segments of a sphere with different velocities linearly spaced between the minimum and maximum values: 2000 km s$^{-1} < v_{\mathrm{SN}} < 4800$ km s^{-1}. The lightcurve first turns on when the slowest ejecta ($v_{\mathrm{SN,min}} = 2000$ km s^{-1}) is fully reshocked at $t_{\mathrm{delay}} + t_{\mathrm{prop.}}(v_{\mathrm{SN,min}}) = (15 + 7.5) = 22.5$ days. The Smith et al. (2007) data was plotted with the first data point (an upper limit) at $t = 22$ days in order to match our model with the overall rise. The spikes in the lightcurve (dashed line) are due to pieces of the SN ejecta being lit up by the QN shock at different times, which would be smoothed out if the distribution of velocities were continuous. The SN material at lower velocities experiences the QN shock earlier
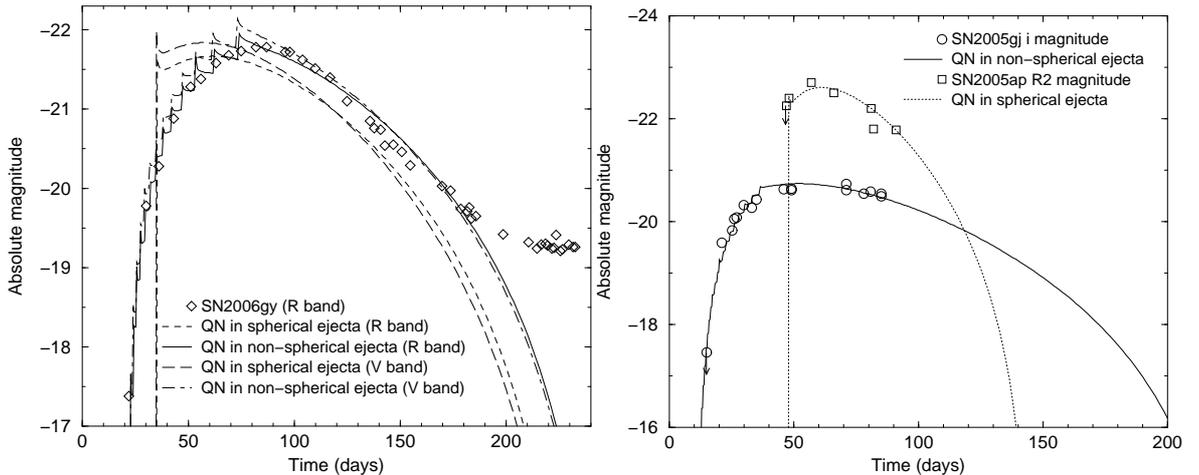
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Figure 1: **Left Panel**: Comparison of the observed absolute R-band light curve of SN2006gy and the R-band and V-band light curves derived from our model (from Leahy & Ouyed, 2008). The dashed (long-dash) line shows the derived R-band (V-band) light curve for a QN explosion inside perfectly spherical SN ejecta. The solid (dash-dot) line shows the derived R-band (V-band) light curve for a QN explosion inside a non-spherically expanding SN ejecta. The SN parameters are: Explosion at $t = 0$, $M_{\mathrm{eje.}} = 60 M_\odot$, $R_0 = 10 R_\odot$, and the QN parameters are $t_{\mathrm{delay}} = 15$ days, $v_{\mathrm{QN}} = 6000$ km s^{-1}, and $T_{\mathrm{QN,0}} = 0.4$ MeV. For the spherical case $v_{\mathrm{SN}} = 3400$ km s^{-1} while for the non-spherical case 2000 kms$^{-1} < v_{\mathrm{SN}} < 4800$ kms^{-1}. The spikes in the derived light curves are due to pieces of the SN ejecta being lit up by the QN shock at different times, which would be smoothed out if the distribution of velocities were continuous. **Right Panel**: Comparison of the absolute i-band light curve of SN2005gj and $R2$-band light curve of SN2005ap with those derived from our model. For SN2005gj, the model is calculated with a QN delay of 10 days after the SN, and a range in SN ejecta speeds of 750 kms$^{-1} < v_{\mathrm{SN}} < 4100$ kms^{-1}. For SN2005ap, the model is calculated with a QN delay of 40 days after the SN, and spherical SN ejecta with speed of $v_{\mathrm{SN}} = 4000$ kms^{-1}. For both models, all other QN and SN parameters were kept the same as for the SN2006gy model.

resulting in larger adiabatic losses and lower peak brightness.

In Figures 2 and 3 we show the double-humped feature predicted by the QN model for SN2006gy, SN2003ma (Rest et al. 2009) and SN2008fz (Drake et al. 2009). We note that the first shock (namely the SN proper) might be too faint to be seen due to the large distance to these SNe. We did not include the ^{56}Ni decay contribution. Adding a few solar masses of ^{56}Ni (i.e. the maximum expected for a $60 M_\odot$ progenitor; Nomoto et al. 2007) will increase the magnitudes of the SN humps to no more
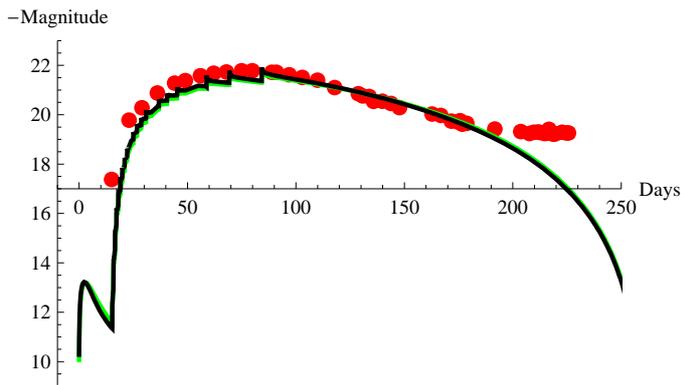
Figure 2: The dual-shock QN application to SN2006gy. The black (green) curve is the R-band (V-band) magnitude calculated from the QN model. Shown is the SN hump preceding the QN one with a delay of 15 days between the two explosions. One of the predictions of the QN is these double hump feature that should accompany extremely luminous SNe. Adding the maximum expected amount of ^{56}Ni for the $60M_\odot$ progenitor will increase the magnitude of the SN hump to no more than ~ -18.

than ~ -18 (which might be slightly above the upper limit for detection). Table 1 summarize the model parameters fits for the five superluminous studied here. For the chosen SN progenitor ($M_{\mathrm{ejec.}} = 60M_\odot$, $R_* = 10R_\odot$, and $T_{\mathrm{SN},0} = 0.3$ MeV), observed superluminous SNe can be well fitted with delays times between the two explosion in the range: days $< t_{\mathrm{delay}} <$ weeks.

3.3 Spectroscopy: *The unusual lines*

Kawabata et al. (2009) found unusual features in the innermost ejecta visible at $t = 394$ days for SN2006gy (i.e. in the late time spectrum; marked with dashed lines in their Figure 5). These lines are not seen in other types of SNe (see their Fig. 9-11), rather resembling Ti and Ca lines. One of the interesting discoveries in Jaikumar et al. (2007) was the smaller peaks appearing around mass numbers $A \sim 44$ (mainly from heavy Ca and Ti isotopes - see Figure 4) and $A \sim 80$ (mainly from Se and Kr and their isotopes) along with production of heavy elements up to the 3rd r-process peak. Such a feature follows from the large neutron-to-seed ratio and strong fission cycling that a QN can provide naturally.

Simulations of r-process nucleosynthesis in the QN model (Jaikumar et al. 2007; Charignon, Ouyed, & Jaikumar 2009) indicate that the elements near the 3rd r-process peak are very efficiently produced when the energy and entropy level are those expected in a QN scenario. For not too small $Y_e \sim 0.12$, these simulations support a strong link between the QN and small peaks appearing around mass numbers $A \sim 44$
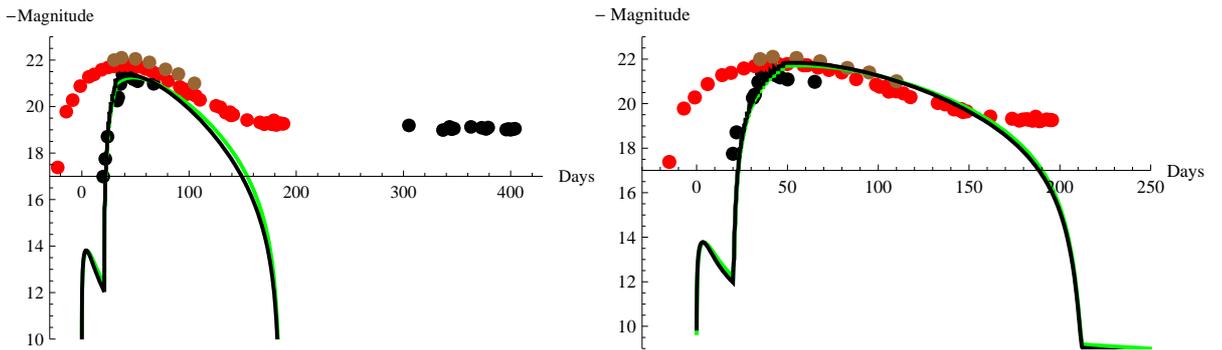
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Figure 3: Observed SN2003ma (top-most black dots) and SN2008fz (bottom-most brown dots). The broader SN2006gy (the red dots in-between) is shown for comparison. Also shown is the predicted SN hump preceding the QN for SN2003ma (in the left panel) and SN2008fz (in the right panel). The left panel shows the late plateau of SN2003ma which we discuss in an upcoming paper (see §3.2 in Leahy&Ouyed (2008) for a discussion of the plateau in SN2006gy). Nickel decay will increase the magnitudes of the SN humps to no more than ~ -18.

(mainly from heavy Ca, Ar and Ti isotopes) and $A \sim 80$ (mainly from Se and Kr and their isotopes; see Figure 4).

The QN ejecta is expected to achieve gamma-ray transparency sooner than SN ejecta since QN progenitors (i.e., neutron stars) lack extended atmospheres. This means that r-process-only nuclei with gamma-decay lifetimes of the order of years (such as ^{137}Cs, ^{144}Ce, ^{155}Eu and ^{194}Os) can be used as tags for a quark star formed in a recent quark nova. The gamma-fluxes from some long-lived radionuclides such as ^{226}Ra, ^{229}Th and ^{227}Ac produced in a QN have been tabulated in Jaikumar et al. (2007). These results provide an observable that can distinguish a QN from a SN, and they also establish a connection to the r-process that can be empirically tested by satellite-based instruments in the very near future.

4 Discussion and Conclusion

4.1 The photon fireball and explosive astrophysics

In core-collapse SNe, neutrinos being the lightest and most weakly interacting particle, carry away 99% of the star's binding energy and drive the explosion. In QNe, neutrinos emitted from the quark core have long diffusion timescales, of order 10-100 ms for $T \sim 20$ MeV (KOJ) and cannot escape before the entire star converts to (u, d, s) matter. With a hadronic crust, the heating effect of the neutrinos implies

SN	t_{delay} (days)	$T_{\text{QN},0}$ (MeV)	$v_{\text{QN,shock}}$ (km/s)	$v_{\text{SN,min}}$ (km/s)	$v_{\text{SN,max}}$ (km/s)
2006gy	10	0.4	6000	2000	4800
2005ap	40	0.4	25000	4000	4000
2005gj	10	0.4	6000	750	4100
2008fz	20	0.9	8000	200	4800
2003ma	30	0.5	8000	2900	2900

Table 1: Dual-shock QNe fits to superluminous SNe. Shown are the delay time between the two explosion (t_{QN}), the initial temperature of the reshocked SN ejecta ($T_{\text{QN},0}$), the shock velocity of the reshocked SN ejecta ($v_{\text{QN,shock}}$) and the range in the SN ejecta's velocities ($v_{\text{SN,min}}$ and $v_{\text{SN,max}}$). The underlying SN parameters, kept fixed for all candidates, are $M_{\text{ejec.}} = 60 M_\odot$, $R_* = 10 R_\odot$, and $T_{\text{SN},0} = 0.3$ MeV. Candidates with $v_{\text{SN,min}} \sim v_{\text{SN,max}}$ were best fit with an almost spherical shell (asphericity not exceeding the 10%).

that the mean free path in the crust is of the order of meters, and mass ejection is of the order of $10^{-5} M_\odot$. Thus, neutrinos are not very efficient in depositing their energy in the outer layers of the star in a short enough time.

For a QN, the suitable agent of explosion are the photons, since the temperature of the quark core is large enough at the time of formation ($\sim 20 - 50$ MeV) to sustain large photon emissivities. If quark matter is in a normal (i.e., non-superconducting) state ($T \geq 50$ MeV), the photon emissivities are extremely large since $T > \hbar\omega_p/k_B$ where $w_p \sim (20 - 25)$ MeV is the plasma frequency of normal quark matter (Usov 2001). The mean free path is small enough to thermalize these photons inside quark matter, and smaller still in the hadronic envelope ($\omega_p(\text{hadronic}) \sim 100$ MeV) so that energy deposition by photons is highly efficient.

If quark matter is superconducting and in the CFL phase, the result is similar. A huge build-up of thermal photons occurs because of medium effects. At $T = 0$, a residual but exact $U(1)$ symmetry ensures that CFL photons travel freely in the quark medium. However, at $T \sim (5 - 50)$ MeV, these photons thermalize due to electromagnetic interactions with charged light Goldstone mesons (Vogt, Rapp & Ouyed 2004; Jaikumar, Prakash & Schäfer 2002) and their mean free path is of order fermis. The resulting emissivity saturates the black body limit at $T \sim 50$ MeV. Compared to the neutrino flux from hot quark matter, the photon flux is from 1-3 orders of magnitude higher for temperatures in MeV-tens of MeV. It follows that energy deposition in the crust is much more efficient for photons than neutrinos. Even a few percent of the photon energy, when deposited in the thin crust of the star, will impart a large momentum to it, leading to strong and ultra-relativistic mass ejection (Ouyed&Leahy 2008). Up to $10^{-2} M_\odot$ can be ejected by the photon fireball, making the QN a highly explosive and luminous astrophysical phenomenon.
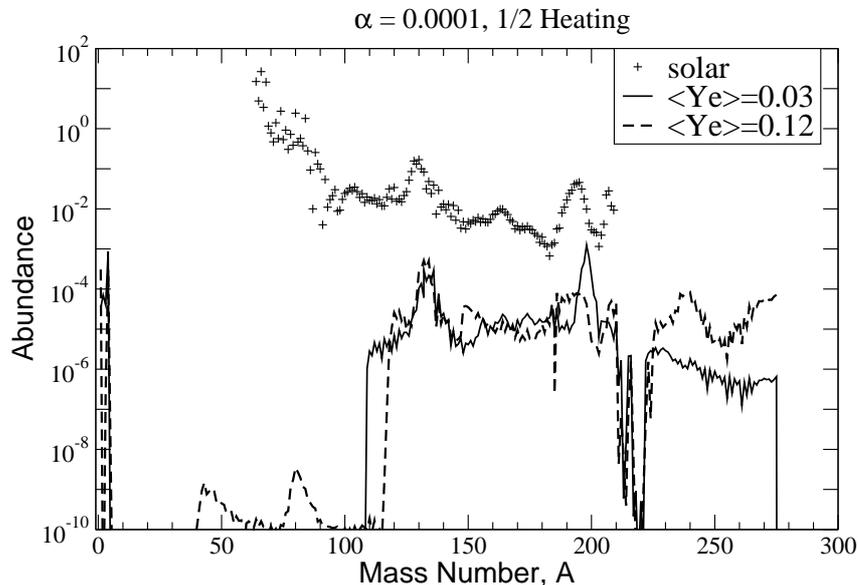
Figure 4: The r-process element abundance distribution as a function of mass number in a QN: parameters of the simulation are fixed to expansion timescale $\tau \sim 0.1\text{ms}$, 50% local energy deposition from nuclear reactions, and mass averaged electron fraction of ejecta $\langle Y_e \rangle$=0.03 and 0.12 as shown (from Jaikumar et al. (2007)). Note the peaks at Hydrogen and Helium. The solar heavy-element abundance is also shown for comparison.

As we have argued on the basis of observations as well, this lends itself naturally to an explanation of the superluminous SNe. Below, we discuss some astrophysical consequences and predictions that follow from the QN.

4.2   The QCD-Astrophysics connection

The discovery of a QN would have tremendous implications for Quark Matter and astrophysics. Among the immediate implications:

- It would confirm that SQM (in a color superconducting, CFL-like, state) exists in a stable state in the universe.

- The separation between the humps in the lightcurve (i.e. $t_{\text{delay}} + t_{\text{prop.}}$) is an estimate of the time delay between the two explosions, t_{delay}. This delay is

intimately linked to the value of the deconfinement density (see Staff, Ouyed, & Jaikumar 2006) which is of relevance to QCD.

- The additional energy deposited by the QN ejecta is an estimate of the energy release during a QN explosion. Since the gravitational energy is transferred to internal and shock energy, superluminous SNe provide a window into the energetics of the phase transition in cool and dense matter.

- QN do not require the existence of extreme mass progenitors (see Appendix C). If the proposed observations reveal the expected sequence of spectroscopic features, our views of the final states of massive stars have to be revised. Even a small fraction of progenitors with masses in the 25-40 $M_\odot$ range undergoing a double explosion is enough to account for the rate of observed superluminous SNe.

- The first results on the production of heavy elements (with $A > 130$) in a QN described in Jaikumar et al. (2007; see also Charignon et al. 2009) were meaningfully compared to the striking r-process pattern seen in several old metal-poor stars. The observed delamination of a QN would make this connection more robust with immediate implications to our modeling of chemical evolution of galaxies and of the IGM. As shown in Ouyed, Pudritz, & Jaikumar (2009), with QNe, a normal initial mass function (IMF) for the oldest stars can be reconciled with the mean metallicity of the early IGM post-reionization. It would be remarkable if the solution to the longstanding problem of heavy-element ($A > 130$) nucleosynthesis and the early IGM metallicity enrichment is intimately linked to the conclusive spectral evolution of a dual-shock QN.

- Yasutake et al. (2005) and Staff et al. (2006) have determined that the evolutionary transition from rapidly rotating neutron stars to quark stars due to spin-down can lead to an event rate of 10^{-4}-10^{-6} per year per galaxy. Similar rates were derived from studies of QNe contributions to r-process material in the Galaxy by Jaikumar et al. (2007) who estimated that 1 out every 1000 neutron stars might have undergone a QN. Since the Galaxy likely contains about 10^8 neutron stars this suggests an average QN rate of 10^{-5} per year per galaxy. Interestingly, the fraction of SN progenitors with mass greater than $60 M_\odot$ can be estimated as $\sim 5 \times 10^{-3}$, using the Scalo (1986) initial mass function for $M > 8 M_\odot$. Using a SN rate of $\sim 10^{-2}$ per year per galaxy, we get $\sim 5 \times 10^{-5}$ per year per galaxy for the explosion rate of massive star ($> 60 M_\odot$). This is, within uncertainties, the same as the QN rate.

4.3 Four predictions

- Two SN-like lightcurves are seen, with the first a normal SN lightcurve, and the second brighter one delayed from the first by by a few days to a few weeks. The shape and peak magnitude of the second lightcurve depend on the delay time (with generally lower peak for shorter delays) and also on the SN envelope mass and SN ejection velocity.

- Two shock breakouts should be observed for the QN vis-a-vis one for a normal SN. Depending on the time delay, this would manifest as two distinct spikes in the X-ray region or a broadening of the first spike for very short delays (< 1 day) between the two explosions. The double shock breakout specific to the QN model is currently being investigated in more details.

- Another tell-tale signature that would clearly distinguish a QN from a SN would be the detection of radioactive elements with lifetimes of order several days or few weeks. Such short-lived elements cannot realistically be detected in SN, since their decay times are too short compared to the gamma transparency of the SN ejecta. But the QN ejecta is relativistic and plows into the SN ejecta at very large speeds, producing the dual shock. If subsequent mixing effects are strong, there is the possibility that some of the short-lived heavy elements could be detected against the background of the late-time (decaying) light curve. Based on the r-process calculations of Jaikumar et al. (2007), we have identified some promising "signature" elements of the dual QN, including but not limited to:^{156}Eu$_{63}$, ^{166}Dy$_{66}$, ^{175}Yb$_{70}$, ^{183}Ta$_{73}$, ^{191}Os$_{76}$, ^{193}Ir$_{77}$, ^{223}Ra$_{88}$, ^{225}Ac$_{89}$. (All of them are γ-active with lifetimes of few days-few weeks): Specifically, gamma decay lines from these elements should be seen in late spectra of superluminous SNe once the photosphere has receded deep into the ejecta.

- As seen from Figure 4, the QN yield will also contain hydrogen and helium. We expect the spectra in dual-shock QNe (superluminous SNe) to include H$_\alpha$ emission lines that should be distinct (delayed) from standard H$_\alpha$ emission usually attributed to preshocked circumstellar material. There are a few caveats attached to this fourth prediction: (i) As can be seen from Figure 4, the hydrogen (and helium) abundance is no higher than the heavy element peaks. Since H and He are two elements whereas the band from A=100 to 250 has 150 elements, H would comprise only 1% by number (i.e. $\sim 10^{-4}$ by mass). Thus there will be no more than $\sim 10^{-4} M_\odot$ of hydrogen in the QN ejecta. Once mixed with the preceding SN material the H might be hard to detect despite its distinctive velocity signature (with line-width $\propto v_{\rm QN}$); (ii) If the H is moving fast outward in a spherical shell, the line-of-sight Doppler velocity will range from $-v_{\rm QN}$ to $+v_{\rm QN}$, so that the line is spread over a wide frequency range and thus be very

faint; (iii) if there is too much H_α emission in the SN associated galaxy, the QN H_α emission line would not be detectable, even if it is at high velocity.

Finally, it should be emphasized that there are several active research fronts on understanding the possible implications of the QN to other outstanding astrophysical phenomena (e.g. gamma-ray bursters, ultra-high energy cosmic rays, re-ionization ect ...). Some of these phenomena have been listed in the "Turner report" which was entitled "*Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century*" (Committee On The Physics Of The Universe, 2003). It would be remarkable for example if the solution to some of these longstanding problems could find answers in the discovery of stable quark matter in the universe via a QN. A Quark-Nova is a phenomenon that would naturally connect quarks with the cosmos; the most powerful explosions in the universe signaling the birth of the tiniest of particles.

A Disaster scenarios and pollution of neutron stars by CFL strangelets

Here, we would like to discuss "myths" related to strange matter and the destruction of the hadronic universe, and the co-existence of neutron and quark stars:

(i) One might argue that if a strangelet comes in contact with a lump of ordinary matter (e.g. the Earth), it could convert ordinary matter to strange matter thus leading to the so-called "ice-nine" disaster scenario. Madsen (2001) showed that the reduction of the number of strange quarks near the surface of a CFL strangelet is energetically preferable, making it positively charged and electrostatically repelled by nuclei. In the interior of a neutron star, neutrons are readily converted since they do not repel the seed of strangelets and, to a first approximation, would instead contribute to the growth of the strangelet cloud eventually converting the entire star.

(ii) The point above implies that pollution by strangelets (e.g. ejected during coalescence of quark stars in binary systems; e.g. Madsen 2005) would have converted all of neutron stars to quark stars. However one can show that because of the stiffness of quark matter compared to neutron matter, the flux of ejected CFL strangelets during binary coalescence is very low and is below current detection limits (see discussion in Appendix A in Ouyed, Pudritz, & Jaikumar , 2009). Thus, at present, the strange

quark matter hypothesis is not inconsistent with observations. The most recent work about strange star binary mergers by Bauswein et. al. (2008) found that for large values of the MIT bag constant, strange stars can co-exist with ordinary neutron stars as they are not converted by the capture of cosmic ray CFL strangelets. Combining their simulations with recent estimates of stellar binary populations, Bauswein et al. (2008) conclude that an unambiguous detection of an ordinary neutron star would not rule out the strange matter hypothesis.

B Color superconductivity: *The Color-Flavor Locked phase*

In theoretical terms, a color superconducting phase is a state in which the quarks near the Fermi surface become correlated in Cooper pairs, which condense. The dominant interaction between quarks is the strong interaction, described by QCD, which is attractive in some channels (the same force that binds quarks together to form baryons). It is thus expected that quarks will form Cooper pairs very readily and that quark matter will generically acquire a condensate of Cooper pairs (Ivanenko& Kurdgelaidze, 1969; Barrois 1977; Bailin& Love, 1984).

Since there are three different colors (red, green, blue) , and three different flavors (up, down, and strange) color superconducting quark matter can come in a rich multiplicity of different possible phases, based on different pairing patterns of the quarks. Thus in forming the Cooper pairs there is a 9 by 9 color-flavor matrix of possibilities in accordance with Fermi statistics (this means the number becomes much less than 81 once the antisymmtery condition is imposed). The differences between these patterns are very physically significant: different patterns break different symmetries of the underlying theory, leading to different excitation spectra and different transport properties. Which type of pairing is favored at which density remains to be answered. Only at the highest densities can perturbative calculations be applied confidently (Rajagopal&Wilczek 2001). For such extreme densities, the mass of the strange quark is negligible compared to the baryonic chemical potential, leading to the same density of the three flavors u, d and s quarks. Consequently, it also implies that the CFL phase is naturally electrically neutral. In this special regime, it is found that the color-flavor-locked (CFL) quark pairing, in which all three flavors participate symmetrically (with total zero momentum), is favored. The CFL phase is so named because the condensate is not separately invariant under color and flavor transformation - it is only under a combined transformation of color and flavor (a "locking") that it remains invariant. CFL quark matter has many special properties, including the fact that chiral symmetry is broken by a new mechanism: the quark pairs themselves, instead of the more conventional chiral condensate. These properties of the CFL phase have interesting implications to astrophysics such as the generation

of a photon fireball (see discussion in §4.1) which was shown to be of relevance to gamma-ray bursters (Ouyed, Rapp, & Vogt, 2005).

B.1 The Meissner Effect

In superconducting metals, the condensate of Cooper pairs of electrons is charged (breaking the charge symmetry), and as a result the photon, which couples to electric charge, becomes massive. Superconducting metals therefore contain neither electric nor magnetic fields (the Meissner effect). In color superconductivity, since pairs of quarks cannot be color-neutral, the resulting condensate will break the local color symmetry, making the gluons massive. As the photon enters the superconducting quark, it sees the electric charge of the quark. The quark charge is related to flavor via the vector part of the flavor symmetry, but since the flavor symmetry is locked to color in the CFL phase, so the photon will indirectly also see the color charge of the quark. This is equivalent to photon-gluon mixing. The photon itself does not become massive, but mixes with one of the gluons (the eight) to yield a new massless "rotated photon" which has no Meissner effect living happily inside the CFL (Alford et al. 2000).

The conclusion above led to the believe that the magnetic field expulsion in CFL quark stars is unlikely to occur. However this might not be totally true. For example, while most color superconductors (with Spin-0 pairing) are not electromagnetic superconductors because of the "rotated electromagnetism", it is not the case in Spin-1 color superconductors where the Meissner effect is real (e.g. Schmitt et al. 2003). There are other reasons one should expect magnetic field expulsion in CFL quark stars. In a rotating CFL quark star (the QN compact remnant) rotational vortices are also formed (since the CFL phase is a superfluid). The attractive force between the magnetic field confined to the rotational vortices and the one in the bulk matter would lead to expulsion of the bulk magnetic field as the star spins-down and expels vortices. This is equivalent to an effective Meissner-like effect with interesting implications to cooling of compact stars (see Niebergal et al. 2009 for more details).

C Progenitors of dual-shock Quark-Novae

The fit to the observed light curve of the superluminous SNe studied here assume QNe progenitor mass in the $(40\text{-}60)M_\odot$ range. However, one can employ the parameter degeneracy in that fit to examine the dual-shock scenario with the more conservative mass range of $(25\text{-}40)M_\odot$ which is more in line with the literature (e.g. Heger et al. 2003; Nakazato et al. 2008) which suggests prompt BH formation above $40M_\odot$. According to Ouyed et al. (2009), the shock efficiency varies with the SN envelope density as as $\rho_{\rm env.}^2$ with the mean SN envelope density given by $\rho_{\rm env} \propto M_{\rm env.}/R_{\rm env.}^3$. If

we choose $30M_\odot$ instead of $60M_\odot$ for the progenitor of the SN, and demand the same efficiency, we find that the collision radius should be $R_{30} = (30/60)^{1/3} \times R_{60} \sim 0.8 \times R_{60}$ and the delay time $t_{\text{delay},30} = 0.8 t_{\text{delay},60}$; i.e. time delays shorter by 20%. It should be noted however that the effect of the fireball in the CFL phase (Ouyed, Rapp, & Vogt, 2005) has not been taken into account in any of these simulations, which means the range 25-40$M_\odot$ could be somewhat underestimated.

References

[1] Alcock, C., Farhi, E., & Olinto, A. 1986, ApJ, **310**, 261

[2] Aldering, G., et al. 2006, ApJ, 650, 510

[3] Alford, M. G., K., Rajagopal, & F. Wilczek, F 1998, Phys. Lett. B, 422, 247

[4] Alford, M. G., Rajagopal, K., & Wilczek, F. 1999, Nucl. Phys. B. 537, 443

[5] Alford, M., Berges, J., & Rajagopal, K. 2000, Nuclear Physics B, 571, 269

[6] Bailin, D., & Love, A. 1984, Phys. Rept. 107, 325

[7] Barrois, B. 1977, Nucl. Phys. B129, 390

[8] Bauswein, A., Janka, H. -., Oechslin, R., Pagliara, G., Sagert, I., Schaffner-Bielich, J., Hohle, M. M., & Neuhaeuser, R. 2008, arXiv:0812.4248

[9] Bodmer, A. R. 1971, Phys. Rev. D, 4, 1601

[10] Charignon, C., Ouyed, R., & Jaikumar, P. 2009, in preparation.

[11] Committee On The Physics Of The Universe, B. O. P., Astronomy, D. O. E., & Physical Sciences, N. R. C. O. T. N. A. 2003, Connecting quarks with the cosmos : eleven science questions for the new century / Committee on the Physics of the Universe, Board on Physics and Astronomy, Division on Engineering and Physical Sciences, National Research Council of the National Academies. Washington, D.C. : National Academies Press, c2003 [http://adsabs.harvard.edu/abs/2003cqwc.book.....C]

[12] Drago, A. and Lavagno, A. and Parenti, I. 2007, ApJ 659, 1519

[13] Drake, A. J., et al. 2009, arXiv:0908.1990

[14] Haensel, P., Zdunik, J. L., & Schaefer, R. 1986, A&A, 160, 121

[15] Heger, A., & Woosley, S. E. 2003, Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop Celebrating the First Year of the HETE Mission, 662, 214

[16] Heger, A. et al. 2003, ApJ, 591, 288

[17] Horvath, J. E., & Benvenuto, O. G., 1988, Phys. Lett. B, 213, 516

[18] Ivanenko, D. D., & Kurdgelaidze, D. F. 1969, Lett. Nuovo Cim. IIS1, 13

[19] Jaikumar, P., Prakash, M., and Schäfer, T. 2002, Phys. Rev. D66, 063003

[20] Jaikumar, P., Meyer, B. S., Otsuki, K., & Ouyed, R. 2007, A&A, 471, 227

[21] Jaikumar, P., Rapp, R., & Zahed, I. 2002, Phys. Rev. C65, 055205

[22] Kawabata, K. S. et al. 2009, arXiv:0902.1440

[23] Keränen, P., Ouyed, R., & Jaikumar, P. 2005, ApJ, 618, 485

[24] Leahy, D.A. and Ouyed, R. 2008, MNRAS, 387, 1193

[25] Lugones, G., Benvenuto, O. G., & Vucetich, H. 1994, Phys. Rev. D 50, 6100

[26] Madsen, J. 2001, Physical Review Letters, 87, 172003

[27] Madsen, J. 2005, Phys. Rev. D, 71, 014026

[28] Margetis, S. et al. 2000, Annu. Rev. Nucl. Part. Sci., 50, 299

[29] Meynet, G., & Maeder, A. 2003, A&A, 404, 975

[30] Nagle, J. L. and Müller, B. 2006, Ann. Rev. Nucl & Part. Sci 56, 93

[31] Nakazato, K., Sumiyoshi, K., & Yamada, S. 2008, Phys. Rev. D, 77, 103006

[32] Niebergal, B., Ouyed, R., Negreiros, R., & Weber, F. 2009, arXiv:0906.3043

[33] Nomoto, K., et al. 2007, arXiv e-prints, 707, arXiv:0707.2187

[34] Ofek, E. O., et al. 2007, ApJL, 659, L13

[35] Olinto, A. 1987, Phys. Lett. B 192, 71

[36] Ouyed, R., Dey, J., & Dey, M. 2002, A&A, 390, L39

[37] Ouyed, R., Keränen, P., & Maalampi, J. 2005, ApJ, 626, 389

[38] Ouyed, R., Rapp, R., & Vogt, C. 2005, ApJ, 632, 1001

[39] Ouyed, R., Leahy, D., Staff, J., & Niebergal, B. 2009, Advances in Astronomy, 2009, 1 [astro-ph/0705.1240]

[40] Ouyed, R., & Leahy, D. 2009, ApJ, 696, 562

[41] Ouyed, R., Pudritz, R. E., & Jaikumar, P. 2009, ApJ, 702, 1575, [astro-ph/0811.0041

[42] Petrovic, J., Pols, O., & Langer, N. 2006, A&A, 450, 219

[43] Quimby, R.M., et al. 2007, ApJL, 668, L99

[44] Rajagopal, K., & Wilczek, F. 2001, Physical Review Letters, 86, 3492

[45] Rapp, R., Schafer, T., Shuryak E., & Velkovsky, M. 1998, Phys. Rev. Lett., 81, 53

[46] Rest, A., et al., 2009, arXiv:0911.2002

[47] Scalo, J. M. 1986, Fundamentals of Cosmic Physics, 11, 1

[48] Schmitt, Q., Wang, Q., & Rischke, D. H. 2003, Phys. Rev. Lett., 91, 242301

[49] Smith, N., et al. 2007, ApJ, 666, 1116

[50] Staff, J.E., Ouyed, R., & Jaikumar, P. 2006, ApJL, 645, L145

[51] Staff, J., Ouyed, R., & Bagchi, M. 2007, ApJ, 667, 340

[52] Staff, J., Niebergal, B., & Ouyed, R. 2008, MNRAS, 391, 178

[53] Usov, V. V., 2001, ApJ 550, L179

[54] Vogt, C., Rapp, R., & Ouyed, R. 2004, Nuclear Physics A, 735, 543

[55] Witten, E. 1984, Phys. Rev. D, 30, 272

[56] Yasutake, N., Hashimoto, M., & Eriguchi, Y. 2005, Progress of Theoretical Physics, 113, 953