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Quark-Nova

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Abstract. We explore the scenario where the core of a neutron star (having experienced a transition to an up and down quark phase) shrinks into the equilibrated quark object after reaching strange quark matter saturation density (where a composition of up, down and strange quarks is the favored state of matter). The overlaying (envelope) material free-falls following the core contraction releasing upto 10^{53} ergs in energy as radiation, partly as a result of the conversion of envelope material to quarks. This phenomena, we named Quark-Nova, leads to a wide variety of ejectae ranging form the Newtonian, "dirty" to the ultra-relativistic fireball. The mass range of the corresponding compact remnant (the quark star) ranges from less than 0.3 $M_{\odot}$ up to a solar mass. We discuss the connection between Quark-Novae and Gamma ray bursts and suggest the recently studied GRB011211 event as a plausible Quark-Nova candidate.

Key words. dense matter – gamma ray: bursts – stars: interior

1. Introduction

Recent and fresh observational data collected by the new generation of X-ray and γ-ray satellites suggest that the compact objects associated with the X-ray pulsars, the X-ray bursters, particularly the SAX J1808.4-3658 (Li et al. 1999) are good quark stars candidates. If quark stars do exist in nature then how do they form? They have been speculated to form directly during or shortly after some supernova (SN) explosion when the central density of the proto-neutron star is high enough to induce phase conversion to quark matter (e.g., Dai et al. 1995; Xu et al. 2000). Another plausible scenario involves converting neutron stars into quark stars (Olinto 1987; Cheng & Dai 1996; Bombaci & Datta 2000). Here we explore the scenario where the quark matter core contracts and shrinks to the corresponding stable compact/quark object. While this has already been considered in the literature (e.g., Rosenhauer et al. 1992; Ma & Xie 1996), in our model the core shrinks as to physically separate from the overlaying material (we refer to as the envelope). This approach, also leading to quark star formation, offers a new and richer dynamics and allows us to develop the concept of Quark-Nova (QN).

2. Strange matter mixture and quark stars

Strange matter, or *(u, d, s)*, mixture (a composition of up, down and strange quarks, hereafter SQM) is traditionally modeled with an equation of state (EOS) based on the MIT-bag model (Farhi & Jaffe 1984). Here, for illustration purposes, we choose to use the EOS as suggested in Dey et al. (1998) with the binding energy versus density of such a system shown in Fig. 1. One finds that from about $3\rho_{\rm N}$ to $7\rho_{\rm N}$ ($\rho_{\rm N}$ is the nuclear matter saturation density) the *(u, d, s)* mixture has more binding energy than ^{56}Fe saturating around $5\rho_{\rm N} \equiv \rho_{\rm ss}$ with an energy about $B_{\rm conv.} \sim 50$ MeV per baryon less than ^{56}Fe and is therefore very stable.

The possible existence of quark stars (specifically of strange star; SSs), is a direct consequence of the above described conjecture that SQM may be the absolute ground state of strong interacting matter rather than ^{56}Fe (Bodmer 1971; Witten 1984; Alcock et al. 1986). Figure 2 shows the SS mass-radius plane resulting from the EOS described in Dey et al. (1998). SSs can acquire masses up to 1.44 $M_{\odot}$, with radii up to 7.06 km (for non-rotating stars). However there is no lower limit on their size (mass) since they would be bound by the strong interaction even in the absence of gravity. Among their features (Alcock et al. 1986; Glendenning 1997) that are relevant to our present model:

i) The density at the surface changes abruptly from zero to $\rho_{\rm ss}$. The abrupt change (the thickness of the quark surface) occurs within about 1 fm, which is a typical strong interaction length scale.

ii) The electrons being bound to the quark matter by the electro-magnetic interaction and not by the strong force, are able to move freely across the quark surface extending up to $\sim 10^3$ fm above the surface of the star. Associated with this electron layer is a strong electric field (5×10^{17} V/cm) which would prevent ionized matter from coming into direct contact with the surface of the star. Note that free neutrons (or neutral matter in

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general) can easily penetrate the Coulomb barrier and gravitate to the surface of the star; they are readily absorbed and converted to quark matter.

3. Quark-Nova collapse

From the calculations by Gentile et al. (1993), the phase transition to a state with the up and down quarks would take place in the inner core (with mass $M_\mathrm{c} < 0.3\ M_\odot$ and radius $R_\mathrm{c} < 1$ km) where matter is homogeneous ($\sim\rho_\mathrm{c}$); it is this portion of the star which we discuss next.

3.1. Core contraction

Take a neutron star (hereafter NS, of mass M_NS) which experienced an increase in their central density above deconfinement values (ρ_d; that is $\rho_\mathrm{c} > \rho_\mathrm{d}$) – following a spin-down history or as a direct result of a SN explosion (see Ma 2002 for a recent discussion). Conversion of (u, d) matter to (u, d, s) takes place via weak interactions where non-leptonic (for example, $u + d \rightarrow u + s$) process is of greater rate (Anand et al. 1997; Olinto 1987; Heiselberg et al. 1991). If the density of the core does not exceed ρ_ss then it will never undergo transition into the lower energy branch of the matter. The NS remains a contaminated stable neutron star namely, a hybrid star with a core density lying between ρ_d and ρ_ss (e.g. Chap. 8 in Glendenning 1997). Only when ρ_ss is reached can a QN occur. We mention that while in the case of a proto-NS the trapped neutrinos will shift the possible onset of the phase transition to SQM to higher densities, with respect to the case of a cold and neutrino-free NS, the basic idea presented below remains the same.

The speed of propagation of the conversion/contamination front and its dynamics are limited by the low weak rate of at which the quarks diffuse. As such, the front propagation might be considered slow compared to the conversion (the conversion into SQM occurs within a very short period of time $\sim 10^{-7}$ s; Dai et al. 1995) leading to the interesting situation where the core density exceeds ρ_ss much before the rest (upper layers) of the star. A scenario where the core would shrink to the corresponding stable bare SQM object.

The radius of the contracted core we can estimate as $R_\mathrm{ss}/R_\mathrm{core} \simeq (\rho_\mathrm{c}/\rho_\mathrm{ss})^{1/3}$. Given our fiducial values $\rho_\mathrm{ss} \simeq 5\rho_\mathrm{N}$ and $\rho_\mathrm{c} \sim 2\rho_\mathrm{N}$ (for a canonical 1.44 $M_\odot$ and standard 10 km radius generic neutron star) the core of the NS would shrink by as much as 30%. The maximum gravitational energy released is thus $(0.3\ M_\odot c^2)\Delta R/R_\mathrm{c} \sim 10^{53}$ ergs; although very large[1] would be mostly carried out by neutrinos and only a very tiny part of it would be released as radiation (Janka & Ruffert 1996).

3.2. Envelope collapse and the neutron drip sphere

Because of the density contrast between the core and the overlaying material ($\sim\rho_\mathrm{N}$), the envelope free-fall time ($t_\mathrm{ff,env.}$) is longer than the core contraction time ($t_\mathrm{ff,ss}$). Simple considerations imply $t_\mathrm{ff,env.}/t_\mathrm{ff,ss} \sim \sqrt{\rho_\mathrm{ss}/\rho_\mathrm{N}} \sim \sqrt{5}$ and the core physically separates from the overlaying material. The infalling envelope material would consist of the neutral part ($\rho_\mathrm{env.} > \rho_\mathrm{drip} = 4.3 \times 10^{11}$ g/cc with ρ_drip the neutron drip density) the ionized plasma part of the envelope material ($\rho_\mathrm{env.} < \rho_\mathrm{drip}$) and the upper solid layers (the crust). The Coulomb barrier of the newly formed quark star which is of the order of $E_\mathrm{C} \simeq 15$ MeV (Alcock et al. 1986) makes the QN collapse very intricate. Indeed, the charged envelope material (including the crust) will be subject to the tremendous Coulomb polarizing force. One might argue that the kinetic energy of a proton when accreted ($\sim Gm_\mathrm{p}M_\mathrm{ss}/2R_\mathrm{ss} \sim 100$ MeV where m_p is the proton mass and G the gravitational constant) is large enough to overcome such a barrier, however, it is likely that the kinetic energy will be radiated away via heat (Frank et al. 1992) before reaching the neutron drip sphere. In this case the energy per accreted proton is reduced below the Coulomb barrier as to halt the infalling material leaving it suspended ("polarized up") a few hundred Fermi above the surface of the SQM core. As we show below, the energy released during conversion of the neutrons is enough to expel any ionized material that might have been left suspended above the newly formed SS as to leave it naked/bare.

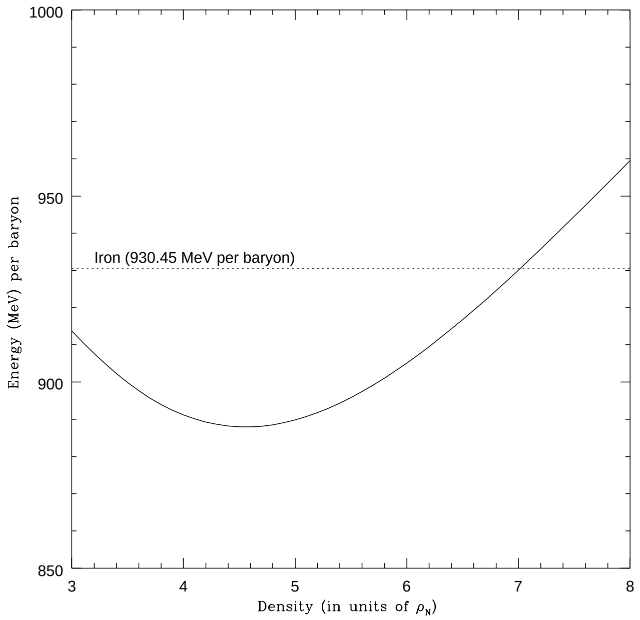

Fig. 1. Energy per baryon for SQM in terms of the density as modeled by Dey et al. (1998). The horizontal dotted line shows the energy per baryon in ^{56}Fe. At high density ($\sim 5\rho_\mathrm{N}$), SQM with its lower energy is the preferred state of matter.

4. Energetics

During envelope collapse we shall have tremendous energy release as radiation. First, is the gravitational binding energy which is released during the first stage of the collapse (onto the neutron drip line), followed by the conversion energy. The neutrons not subject to the Coulomb barrier will continue

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[1] Detailed calculations which includes the various details of the neutron star and SS structural properties can be found in Bombaci & Datta (2000; their Fig. 2 in particular) leading to similar numbers.

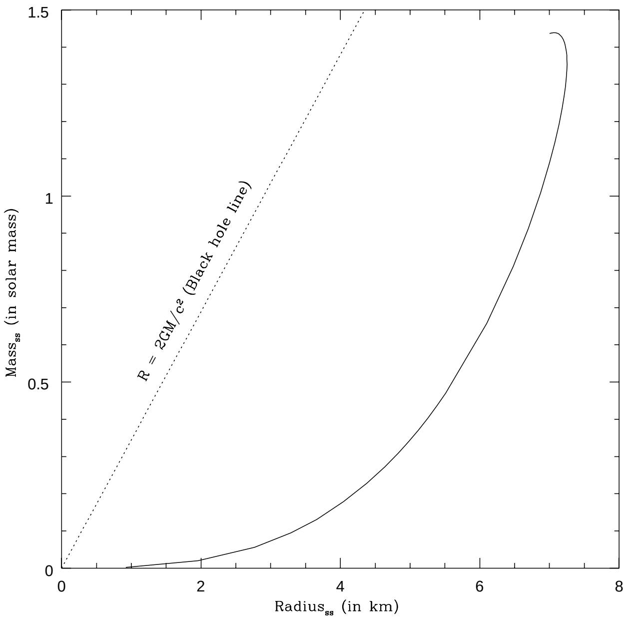

Fig. 2. The mass-radius relation for non-rotating SSs (Dey et al. 1998).

their fall and be be converted to SQM; *the envelope is essentially squeezed out of its neutral component*.

4.1. Accretion energy

The accretion energy can be written as,

$$E_{\rm acc.} \simeq \eta_{\rm acc.}\, M_\odot c^2 \left(\frac{M_{\rm env.}}{M_\odot}\right)\left(\frac{R_{\rm Schw.,ss}}{R_{\rm ss}}\right). \quad (1)$$

In general, $R_{\rm Schw.,ss}/R_{\rm ss} \simeq 1/2$ (Fig. 2) which leave us with,

$$E_{\rm acc.} \simeq \frac{\eta_{\rm acc.}}{2}\, M_\odot c^2 \left(\frac{M_{\rm env.}}{M_\odot}\right). \quad (2)$$

Since the drip line radius does not refer to a "hard" surface but only to a region into which matter can fall before it is squeezed out of its neutrons, it is far from clear on the value of $\eta_{\rm acc.}$ one needs to adopt. It might seem appropriate as a first approximation to take the accretion efficiency of SSs to lie close to that of black holes ($\eta_{\rm BH} \sim 0.1$) and of neutron stars ($\eta_{\rm NS} \sim 0.15$); that is $\eta_{\rm acc.} \sim 0.1$.

4.2. Conversion energy

Each neutron converted to SQM is accompanied by a photon of energy $B_{\rm conv.}$. The conversion energy is therefore

$$E_{\rm con.} \simeq \frac{M_{\rm env.}}{(m_{\rm n} - B_{\rm nuc.}/c^2)}\, B_{\rm conv.}\ {\rm MeV}, \quad (3)$$

where $m_{\rm n}$ is the baryon mass and $B_{\rm nuc.}$ the nuclear binding energy. Equation above is best written as

$$E_{\rm con.} \simeq \eta_{\rm conv.} \left(\frac{M_{\rm env.}}{M_\odot}\right) M_\odot c^2, \quad (4)$$

where $\eta_{\rm conv.} = B_{\rm conv.}/(m_{\rm n}c^2 - B_{\rm nuc.})$ is the *strangeness conversion efficiency* estimated to be $\eta_{\rm conv.} \sim 0.1$ given $B_{\rm conv.} \simeq 50$ MeV.

The energy released in the QN is thus

$$E_{\rm QN} = \eta_{\rm QN} M_\odot c^2 \left(\frac{M_{\rm env.}}{M_\odot}\right), \quad (5)$$

where

$$\eta_{\rm QN} = \left(\frac{\eta_{\rm acc.}}{2} + \eta_{\rm conv.}\right). \quad (6)$$

Thus,

$$E_{\rm QN} \simeq 2\times 10^{53}\ {\rm ergs}\left(\frac{M_{\rm env.}}{M_\odot}\right)\left(\frac{\eta_{\rm QN}}{0.15}\right), \quad (7)$$

which can be as high as $\simeq 10^{53}$ ergs.

5. Quark-Nova features

5.1. QN ejecta and compact remnant

The fireball's radiation energy density aT^4 ($T = B_{\rm conv.} \sim 50$ MeV) by far exceeds that of the gravitational energy density in the envelope ($GM_{\rm ss}\rho_{\rm env.}/R_{\rm ss}$). Some envelope material and any matter that might ended suspended above the neutron drip sphere is thus loaded into the fireball making up the QN ejecta. The corresponding Lorentz factor can be written as

$$\Gamma_{\rm QN} = \frac{E_{\rm QN}}{M_{\rm ejec.}c^2} \sim \left(\frac{\eta_{\rm QN}}{\nu}\right), \quad (8)$$

where ν defines the amount of ejected material ($M_{\rm ejec.} = \nu M_{\rm env.}$). The QN ejecta could lead to a wide variety of ejectae (with different Lorentz factors) ranging from a Newtonian, "dirty" to an ultra-relativistic fireball.

The compact remnant (the quark star) mass is mainly dependent on the amount of envelope material that falls onto the core and acquires a mass in the $M_{\rm c} < M_{\rm ss} < M_{\rm NS}$ range. An efficient envelope extraction would lead to a light star with $M_{\rm ss} < 0.3\, M_\odot$. Note that any fallback material from the QN ejecta would end up as a fossil disk material[2] which if channeled to the polar caps could later form a crust (recall that the disk material is globally charged, Xu et al. 2000).

5.2. QN rate

The QN rate can be expressed as

$$R_{\rm QN} = \zeta\, R_{\rm Ma} \quad (9)$$

where

$$R_{\rm Ma} \simeq 10^{-5} \left(\frac{P_{\rm i}}{20\ {\rm ms}}\right)\left(\frac{R_{\rm NS}}{10^{-2}}\right) {\rm yr}^{-1}\ {\rm galaxy}^{-1}, \quad (10)$$

is the rate at which NSs undergo a phase transition to quark matter in the core (see Ma 2002). $R_{\rm NS}$ is the neutron star birth rate and $P_{\rm i}$ the initial spin of a neutron star. The factor ζ represents the fraction of neutron stars that will undergo the transition to the $\rho_{\rm ss}$ density following deconfinement in the core. We expect ζ to be small making the QN a very rare event. A value for ζ is suggested below.

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[2] The newly formed quark star would have spun up during the contraction naturally offering some angular momentum.

5.3. The Gamma Ray Burst connection?

The QN as we have seen would lead to the formation of hot quark stars (the collapse and conversion process would heat up the star to high temperatures). In Ouyed & Sannino (2002) and Ouyed (2002, for a recent review) we explained how Gamma ray bursts (GRBs) might result from the evaporation of such stars into photons. Such a process as we showed is triggered when quark matter phase transitions come into play at the surface of the star. As the quark star (with surface temperatures above a few tens of MeV) cools it enters the so-called 2 flavor color superconductivity (2SC) phase where glueballs decay into photons (the fireball; Ouyed & Sannino 2001) consuming most of the star in this process. It is interesting to note from Eq. (10) that $\zeta \sim 0.1$ would imply QN rate of *one per million year per galaxy* in agreement with the GRB rate derived from BATSE[3] measurements. This might be an indication that this aspect of our model warrants further study.

5.4. The QN-SN connection: **GRB 011211***?*

If deconfinement (and later $\rho_{\rm ss}$) happens late following a spin-down history then the collapse would occur much after the SN event with no QN-SN interaction. On the other hand, if deconfinement happens during or shortly after the SN event (e.g. for very massive progenitors), the SN is then expected to be followed by the QN. The time delay between the two events (the time it takes the core to reach the critical density $\rho_{\rm ss}$) could vary from seconds to days depending on the conditions in the core of the proto-NS before contraction (such as the temperature and density) and the details of the spread of contamination/conversion front.

Eventually, the QN-ejecta catches up with the dense SN-ejecta which is heated up producing emission. QNe would thus be detected indirectly by their effect on the preceding SNe ejectae. In the case where the QN-ejecta consists of a hot fireball ($v \ll 1$) and the QN occurs within a few days after the SN, the latter is caught up when the expanding QN-ejecta is in its X-ray phase (the fireball afterglow phase; Piran 1999). The dense SN-ejecta when heated up would then produce X-ray emission. Such a signature might have been observed in the GRB011211 case (Reeves et al. 2002) where the authors conclude that the measured X-ray emission is best explained as an emission from SN material illuminated by a GRB which occurred a few days following the SN explosion. Given its features, we are tempted to suggest GRB011211 as a plausible QN candidate.

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[3] The Burst and Transient Source Experiment detector on the COMPTON-GRO satellite observes on average one burst per day. This corresponds, with the simplest model – assuming no cosmic evolution of the rate – to about once per million years in a galaxy (Piran 1999).