Low-Mass X-Ray Binaries with Strange Quark Stars

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Received 2012 September 10; accepted 2012 November 19; published 2012 December 7

ABSTRACT. Strange quark stars (SSs) may originate from accreting neutron stars (NSs) in low-mass X-ray binaries (LMXBs). Assuming that conversion of NS matter to SSs occurs when the core density of accreting NS reaches the density of quark deconfinement, \(\sim 5\rho_0\), where \(\rho_0 \sim 2.7 \times 10^{14} \text{ g cm}^{-3}\) is nuclear saturation density, we investigate LMXBs with SSs (qLMXBs). In our simulations, about 0.1–10% of LMXBs can produce SSs, which greatly depends on the masses of nascent NSs and the fraction of transferred matter accreted by the NSs. If the conversion does not affect binary systems, LMXBs evolve into qLMXBs. We find that some observational properties (spin periods, X-ray luminosities and orbital periods) of qLMXBs are similar to those of LMXBs, and it is difficult to differentiate between them. If the conversion disturbs the binary systems, LMXBs can produce isolated SSs. These isolated SSs could be submillisecond pulsars, and their birthrate in the Galaxy is \(\sim 5–70 \text{ Myr}^{-1}\).

1. INTRODUCTION

There are at least three different kinds of compact stars in the universe: white dwarfs (WDs), neutron stars (NSs), and black holes. Witten (1984) suggested the possible existence of compact objects consisting of strange quark matter. Due to strange quark matter being absolutely stable, Haensel et al. (1986) and Alpar (1987) considered that glinting radio-pulsars are NSs and not strange quark stars (SSs). Madsen (1988) suggested that SSs can not be formed directly in supernovae,4 or else they would eventually contaminate the entire Galaxy. Kluzniak (1994) suggested that SSs could exist as millisecond pulsars. Due to the fast rotation and thermonuclear bursts, Li et al. (1999) suggested that the SAX J1808.4-3658 is a good SS candidate. These SSs can be formed in low-mass X-ray binaries (LMXBs) via an accretion-triggered phase transition of NS matter to SS matter (Cheng & Dai 1996).

The phase transition requires the formation of a strange matter seed in the NS. The strange matter is produced through the neutron matter at a critical density. Serot & Uechi (1987) pointed out that the central density of an \(1.4 M_\odot\) NS with a rather stiff equation of state is sufficiently lower than the critical density. Based on the modern equations of state in Wiringa et al. (1988), Cheng & Dai (1996) estimated that NSs with \(1.4 M_\odot\) must accrete matter of \(\sim 0.5 M_\odot\) for their central densities to reach the deconfinement density. Once the above condition is satisfied, the phase transition occurs.

Olinto (1987) proposed that the process of strange matter swallowing the neutron matter is a slow mode. However, Horvath & Benvenuto (1988) showed that it is hydrodynamically unstable. Cheng & Dai (1996) proposed that the conversion of neutron matter should proceed in a detonation mode and could be accompanied by a gamma-ray burst. Ouyed et al. (2002) suggested that there is a quark-nova when the core of a NS (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). In their model, the energy released as radiation in a quark-nova is up to \(10^{53} \text{ ergs}\). Ouyed et al. (2011) proposed that the quark novae in LMXBs may be the engines of short gamma-ray bursts.

Based on the above descriptions, it is possible that SSs originate from the hydrodynamically unstable conversion or the slow conversion in LMXBs. Using standard equations of state of neutron-rich matter, Staff et al. (2006) considered that the density of quark deconfinement is \(\sim 5\rho_0\), where \(\rho_0 \sim 2.7 \times 10^{14} \text{ g cm}^{-3}\) is nuclear saturation density. According to the equations of state in Akmal et al. (1998), the gravitational mass of a NS must be \(\sim 1.8 M_\odot\) in order to reach \(5\rho_0\). Therefore, it is very important for our understanding of SSs’ formation to study the mass evolution of NSs in LMXBs.

In this work, by simulating the interaction of a magnetized NS with its environment and utilizing a population synthesis code, we focus on the mass change of NSs in LMXBs and the possibility of NSs converting SSs in LMXBs and investigate the properties of LMXBs with SSs (qLMXBs). In § 2, we present our assumptions and describe some details of the modelling...
algorithm. In § 3, we discuss the main results and the effects of different parameters. In § 4, the main conclusions are given.

2. MODEL

For the simulation of binary evolution, we use rapid binary star evolution code BSE (Hurley et al. 2002), which was updated by Kiel & Hurley (2006). In interacting binaries, NSs can be formed via three channels (e.g., Ivanova et al. 2008; Kiel et al. 2008): (i) Core-collapse supernovae (CCSN) for a star; (ii) Evolution induced collapse (EIC) of a helium star with a mass between 1.4 and 2.5 $M_\odot$, in which the collapse is triggered by electron capture on $^{20}$Ne and $^{24}$Mg (Miyaji et al. 1980); (iii) Accretion-induced collapses (AIC) for an accreting ONeMg WD whose mass reaches the Chandrasekhar limit. Response of accreting ONeMg WD is treated in the same way as the evolution of CO WD (see details in Lü et al. [2009]).

2.1. Mass of Nascent NS

Possibly mass is one of the most important properties of NSs. However, the mass distribution of nascent NSs is not yet well known. In BSE code, the gravitational mass of a nascent NS via CCSN depends on the mass of the CO-core at the time of supernova (Hurley et al. 2000). Figure 1 shows the masses of nascent NSs formed from different initial masses. Some authors assumed that the initial masses of NSs ($M_{\text{NS}}^i$) are 1.4 $M_\odot$ in their works (e.g., Ergma et al. 1998; Podsiadlowski et al. 2002; Nelson & Rappaport 2003). Lattimer & Prakash (2007) showed that the masses of some NSs are lower than 1.4 $M_\odot$. Recently, van der Meer et al. (2007) found that the masses of NSs in SMC X-1 and Cen X-3 are $1.06^{+0.11}_{-0.06}$ $M_\odot$ and $1.34^{+0.16}_{-0.14}$ $M_\odot$, respectively. However, it is well known that most of the accurately measured masses of NSs are near 1.4 $M_\odot$.

In our work, we use the initial masses of NSs via CCSN in Hurley et al. (2000) and $M_{\text{NS}}^i = 1.4 M_\odot$ in different simulations. For NSs via AIC, following Hurley et al. (2000), we take $M_{\text{NS}}^i = 1.3 M_\odot$. Similarly, for NSs via EIC, we also take $M_{\text{NS}}^i = 1.3 M_\odot$.

In addition, a nascent NS receives additional velocity (“kick”) due to some still unclear process that disrupts spherical symmetry during the collapse or later. The dichotomous nature of kicks was suggested quite early by Katz (1975). Observationally, the kick is not well constrained due to numerous selection effects. Currently, high kicks ($\sim$100 km s$^{-1}$) are associated with NSs originating from CCSN, while low kicks ($\sim$10 km s$^{-1}$) are associated with NSs born in EIC and AIC (Pfahl et al. 2002). We apply to core-collapse a NS Maxwellian distribution of kick velocity $\nu_k$:

$$P(\nu_k) = \frac{2}{\pi \sigma_k^2} e^{-\nu_k^2/2\sigma_k^2},$$

Figure 1.—Masses of nascent NSs via CCSN vs. stellar initial masses. The solid line comes from Hurley et al. (2000), and the dashed line means that masses of nascent NSs are equal to 1.4 $M_\odot$.

Variation of $\sigma_k$ between 50 and 200 km s$^{-1}$ introduces an uncertainty $\lesssim$3 in the birthrate of low- and intermediate-mass X-ray binaries (Pfahl et al. 2003). Zhu et al. (2012) discussed the effects of parameter $\sigma_k$ on the LMXBs’ populations. Since in this article we focus on the physical parameters that mostly affect the masses of NSs, we do not discuss the effects of $\sigma_k$ on SSs’ population. Following Lü et al. (2012), we take $\sigma_k = 190$ km s$^{-1}$ in CCSN and $\sigma_k = 20$ km s$^{-1}$ in EIC and AIC.

2.2. Mass of Accreting NS

In LMXBs, NSs accrete the matter from their companions via Roche lobe flows or stellar winds. The interaction of a rotating magnetized NS (single or in a binary system) with surrounding matter has been studied by many authors (e.g., Pringle & Rees 1972; Illarionov & Sunyaev 1975; Ghosh & Lamb 1978; Lovelace et al. 1995, 1999). Using a convenient way of describing NS evolution elaborated by Lipunov et al. (1992) and a recent model for quasishperical accretion including subsonic settling proposed by Shakura et al. (2012), Lü et al. (2012) gave detailed simulations for spin period evolution and matter accretion of NSs in binaries. In this work, we adopt their model. Lü et al. (2012) assumed that all matter transferred is accreted by the NS in an accretor stage. We introduce a parameter $\beta$, which is the fraction of transferred matter accreted by the NS; the rest of the transferred matter is lost from the binary system. The lost matter takes away the specific angular momentum of the prospective donor. The value of $\beta$ has been usually set to 0.5 (Podsiadlowski et al. 1992, 2002; Nelson & Rappaport 2003). In our work, we set $\beta = 0.1, 0.5, 1.0$ in different simulations.
2.3. LMXBs with Nascent SSs

As noted in § 1, when the gravitational mass of a NS reaches \( \sim 1.8 \, M_\odot \), the NS can turn into a SS via a hydrodynamically unstable conversion or a slow conversion. In the former mode, the binary system may be disrupted (Ouyed & Staff 2011), and it becomes two isolated stars. One of them is an isolated SS. However, it is difficult to know the effects of the hydrodynamically unstable conversion on binary systems. Therefore, in our work, we consider two extreme cases: (i) In order to simulate all potential properties of qLMXBs, we assumed all LMXBs are not affected and survive after the conversion, that is, LMXBs become qLMXBs when the masses of accreting NSs are larger than \( 1.8 \, M_\odot \); (ii) We assumed that all LMXBs are disrupted after the conversion, that is, there is no qLMXBs. However, we can discuss the origin of isolated submillisecond pulsars.

In our simulations, if a nascent NS has mass larger than \( 1.8 \, M_\odot \), it is a SS. Therefore, in the paper, qLMXBs include some LMXBs in which the nascent NSs have masses larger than \( 1.8 \, M_\odot \). Lai & Xu (2009) suggested that SSs could have high maximum masses (see Fig. 2 in Lai & Xu [2009]) if they are composed of Lennard-Jones matter. In our work, we assume that the maximum mass of a SS is \( 3.0 \, M_\odot \).

3. RESULTS

We use the Monte Carlo method to simulate the initial binaries. For initial mass function, mass-ratios and separations of components in binary systems, we adopt the distributions used by us in Lü et al. (2006, 2008). We assume that all binaries have initially circular orbits. After a supernova, new parameters of the orbit are derived using standard formulae (e.g., Hurley et al. 2002). It is well known that theoretical models of the population of LMXBs depend on badly known input parameters, such as kick velocity and common envelope treatment (e.g., Pfahl et al. 2003; Zhu et al. 2012). However, in this pioneering study of qLMXBs, we focus on the effects that are important for the masses of NSs: the accretion efficiency of transferred matter, \( \beta \) (\( \beta = 0.1 \), 0.5 and 1.0) and the mass of the nascent NS via CCSN (see Fig. 1). We use \( 1 \times 10^8 \) binary systems in our Monte Carlo simulations.

3.1. Mass Increases of Accreting NSs

Figure 2 gives the mass increases of accreting NSs in LMXBs. According to the assumptions of SSs forming from NSs with masses higher than \( 1.8 \, M_\odot \), about 0.1% (\( \beta = 0.1 \))–10% (\( \beta = 1.0 \)) of LMXBs are qLMXBs in our simulations. This proportion greatly depends on input parameters \( \beta \) and the initial masses of the nascent NSs. In the cases of \( \beta = 1.0 \) and \( \beta = 0.5 \), most of SSs in qLMXBs come from NSs with a low mass of \( 1.4 \, M_\odot \); that is, they have accreted \( \sim 0.4 \, M_\odot \) matter. In the case of \( \beta = 0.1 \), most of SSs in qLMXBs originate from CCSN.

Mass increases of accreting NSs in LMXBs depend on not only input parameter \( \beta \) in this work, but also on orbital periods...
and the NSs’ companions. Zhu et al. (2012) showed that most of the NSs in LMXBs with WD donors have low mass-accretion rates (\(\sim 10^{-12} \, M_\odot \, yr^{-1}\)) and that most of the LMXBs with WD donors are transient. Therefore, the masses of accreting NSs in LMXBs with WD donors hardly reach \(1.8 \, M_\odot\). Less than 10\% (in the case of \(\beta = 0.1\))–0.1\% (in the case of \(\beta = 0.5\), \(M_{\text{NS}} = 1.4 \, M_\odot\)) of qLMXBs have WD donors in our simulations. Most qLMXBs have main sequence donors. From now on, we just discuss the LMXBs and qLMXBs with MS donors.

### 3.2. Properties of qLMXBs

According to our assumption that the conversion of NS matter to SS matter does not affect binary systems, we can simulate some observational properties of LMXBs and qLMXBs and hope to find some differences between them. Then, taking

\[
L_x = \eta M_{\text{NS}} c^2 \approx 5.7 \times 10^{35} \, \text{erg s}^{-1} \left(\frac{\eta}{0.1}\right) \times \left(\frac{M_{\text{NS}}}{10^{-10} \, M_\odot \, yr^{-1}}\right),
\]

where \(\eta \approx 0.1\) is the efficiency of converting accreted mass into X-ray photons. We find that there is not significant difference between accretion rates by NSs or SSs in LMXBs and qLMXBs.

The spin periods of the rotating magnetized NSs mainly depend on their mass-accretion rates (Lü et al. 2012). If accreting SSs are similar to NSs, we can simulate the spin periods of the case of \(\beta = 0.5\) as an example, we discuss some properties of qLMXBs.

X-ray luminosities (mass-accretion rates), spin periods and orbital periods are important parameters of LMXBs. Figure 3 shows the accretion rates by NSs and SSs in LMXBs and qLMXBs and the X-ray luminosities, which are approximated as

Fig. 3.—Distributions of accretion rates (X-ray luminosities) by NSs and SSs in LMXBs and qLMXBs, respectively.

![Fig. 3](image1)

Fig. 4.—Number distributions of the spin periods of NSs and SSs in LMXBs and qLMXBs, respectively. The numbers are normalized to one.

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Fig. 5.—Similar to Figure 2, but for the distributions of the orbital periods \(P_{\text{orb}}\) of qLMXBs and LMXBs vs. the masses of their secondary stars.
accreting SSs. Figure 4 gives the distribution of the spin periods of NSs in LMXBs or SSs in qLMXBs. In general, spin periods of SSs in qLMXBs are shorter than those of NSs in LMXBs.

Figure 5 shows the distributions of the orbital periods $P_{orb}$ of LMXBs and qLMXBs versus the masses of their secondary stars. Similarly, there is not significant difference between qLMXBs and LMXBs.

As the above descriptions show, it is very difficult in our model to differentiate between LMXBs and qLMXBs. The most effective way is to measure the masses of compact objects in LMXBs if the assumption that NSs with masses larger than 1.8 $M_{\odot}$ are SSs is right.

Jonker et al. (2005) suggested that the compact object in 2S 0921-630 (It is a LMXB.) has a mass between $\sim$1.9–2.9 $M_{\odot}$. According to our assumption, the compact object is a SS. However, Steeghs & Jonker (2007) considered that Jonker et al. (2005) overestimated the rotational broadening and that the mass of the compact object in 2S 0921-630 is $\sim$1.44 $M_{\odot}$. The orbital period of 2S 0921-630 is 9.006 ± 0.007 days, and its X-ray luminosity is $\sim$10^{36} erg s$^{-1}$ (Kallman et al. 2003). Results of simulating LMXBs and qLMXBs in our work cover both these observations. Therefore, we can not conclude whether the compact object in 2S 0921-630 is a NS or SS.

Demorest et al. (2010) gave that PSR 1614-2230 has a mass of 1.97 $M_{\odot}$. And, it is a millisecond radio pulsar (Pulsar spin period is 3.15 ms.) in an 8.7 day orbit, and its companion has a mass of 0.5 $M_{\odot}$. Although PSR 1614-2230 is not an X-ray binary, it may come from an X-ray binary. Lin et al. (2011) suggested that PSR 1614-2230 descended from a LMXB very much like Cyg X-2 ($P_{orb} = 9.8$ days, $M_{NS} = 1.7$ $M_{\odot}$ and $M_2 = 0.6$ $M_{\odot}$, see Casares et al. [2010]). As Figure 5 shows, our results cover the positions of orbital periods and the companion masses of Cyg X-2 and radio millisecond pulsar binary PSR 1614-2230. Our work supports that PSR 1614-2230 originates from a LMXB. PSR 1614-2230 may be a SS.

3.3. Submillisecond Pulsars

Weber (2005) suggested that an isolated submillisecond pulsar spinning at $\sim$0.5 ms could strongly hint at the existence of SSs. If the conversion of NS matter to SS matter is hydrodynamically unstable and LMXBs are disrupted, the nascent SSs are isolated. Assuming that one binary with $M_1 \geq 0.8$ $M_{\odot}$ is formed per year in the Galaxy (Yungelson et al. 1993; Han 1998; Hurley et al. 2002), we can estimate that the occurrence rate of hydrodynamically unstable conversion is about 5–70 Myr$^{-1}$.

As Figure 6 shows, the majority of NSs at the beginning of the conversion have spin periods longer than 1 ms. If angular momentum is conserved and no unknown physical mechanic spins up NSs and nascent SSs during the conversion, the spin periods of nascent SSs depend on the change in moment of inertia. Ouyed & Staff (2011) considered that a typical ejected mass of hydrodynamically unstable conversion is $\sim$10^{-3} $M_{\odot}$. Therefore, the change in moment of inertia is determined by the difference in radius between the NS and SS. Ouyed et al. (2002) estimated that the NS could shrink by as much as 30%. Then, many nascent SSs have spin periods of $\sim$0.5 ms in our simulations. However, this result greatly depends on the equations of state of the NSs and SSs, which are poorly known. If the NS only shrinks by as much as 10% (Xu 2012, private communication), it is difficult for the nascent SSs to spin up to 0.5 ms.

4. CONCLUSIONS

Employing the population synthesis approach to the evolution of binaries and using the model of a rotating magnetized NS interacting with surrounding matter, we investigate the mass change of NSs in LMXBs and the possibility of NSs converting SSs in LMXBs. Our results show that about 0.1–10% of LMXBs can produce SSs. These SSs may exist in qLMXBs or be isolated, depending on the physical model for the conversion of NS matter to SS matter.

Our toy model cannot conclude whether there are SSs in the Galaxy and cannot give what properties qLMXBs have. In further work, we need a detailed physical model (equations of state for the NS and SS and the conversion of NS matter to SS matter) to improve our work.

This work was supported by the National Natural Science Foundation of China under Nos. 11063002, 11163005, 10963003 and 11103054, the Natural Science Foundation of Xinjiang under Nos. 2010211B05 and 2011211A104, the Foundation of Huo Yingdong under No. 121107, the Foundation of the Ministry of Education under No. 211198, the program of the light in China’s Western Region (LCWR) (No. XBB5201022), and the Doctor Foundation of Xinjiang University (BS100106).
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