Formation scenarios of strange quark stars

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Abstract The existence of strange quark stars has been proposed many years ago. More recently, the possible co-existence of a first family composed of "normal" neutron stars with a second family of strange quark stars has been proposed as a solution of problems related to the maximum mass and to the minimal radius of these compact stellar objects. We studied the mass distribution of compact objects formed in binary systems and the relative fractions of quark and neutron stars in different subpopulations. According to our results, the main channel for strange quark star formation in binary systems is accretion on a neutron star. The number of double strange quark star systems is rather small with only a tiny fraction which merges within a Hubble time. This drastically limits the strangelets' pollution, and it rules out at least one relevant channel for the transformation of all neutron stars into strange quark stars.

Keywords: methods: statistical – stars: neutron – stars: peculiar – X-rays: binaries

1. Introduction

Strange quark stars (QS) are defined as being composed of strange quark matter, i.e. built of three quarks: up, down, and strange. A neutron star (NS) built of hadronic matter may be perceived as metastable object which converts into a QS when a significant number of hyperons form in its interior. According to the two-families scenario (Drago et al. 2015), when a NS reaches a threshold internal density a deconfinement process occurs, which may have a duration of only 10 seconds. As a result, entire stars becomes a QS and a gravitational mass is significantly lowered (by about 10%), although the barionic mass is conserved.

The two-families scenario therefore predicts that NSs and QSs may coexist in stellar populations. Below a minimal QS mass compact object may be only a NS, whereas above maximal NS mass, only QSs are possible. Between these two limiting values, both Nss and Qss may be present (coexistence range).

A QS in this scenario may form either directly after a supernova explosion (SN), or as a result of a mass accretion onto a NS. In both cases a QS may accrete additional matter and obtain mass significantly above 2 $M_{\odot}$. In the coexistence range we expect more objects in the two-families scenario, then in the one-family scenario, i.e. case in which only NSs exist and QSs are never formed.

In this study, we analyze QS formation routes in the two-families scenario on the base of the results obtained by Wiktorowicz et al. (2017; hereafter W17). Sec. 2 concentrates on theoretical formation scenarios. Sec. 3 briefly describes the methods. Sec. 4 contains results. In Sec. 5 we summarize the paper.

2. Formation scenarios

According to the two-families scenario, a NS becomes a QS when a central density reaches values high enough for hyperons' formation. However, the exact value depends on the applied physics. Therefore, in W17 it was assumed that a NS converts immediately into a QS when a mass threshold is reached. An exemplary conversion is presented in Fig. 1. Two values for deconfinement mass were tested: 1.5 $M_{\odot}$ and 1.6 $M_{\odot}$, which correspond to the non-rotating and strongly rotating NS, respectively.

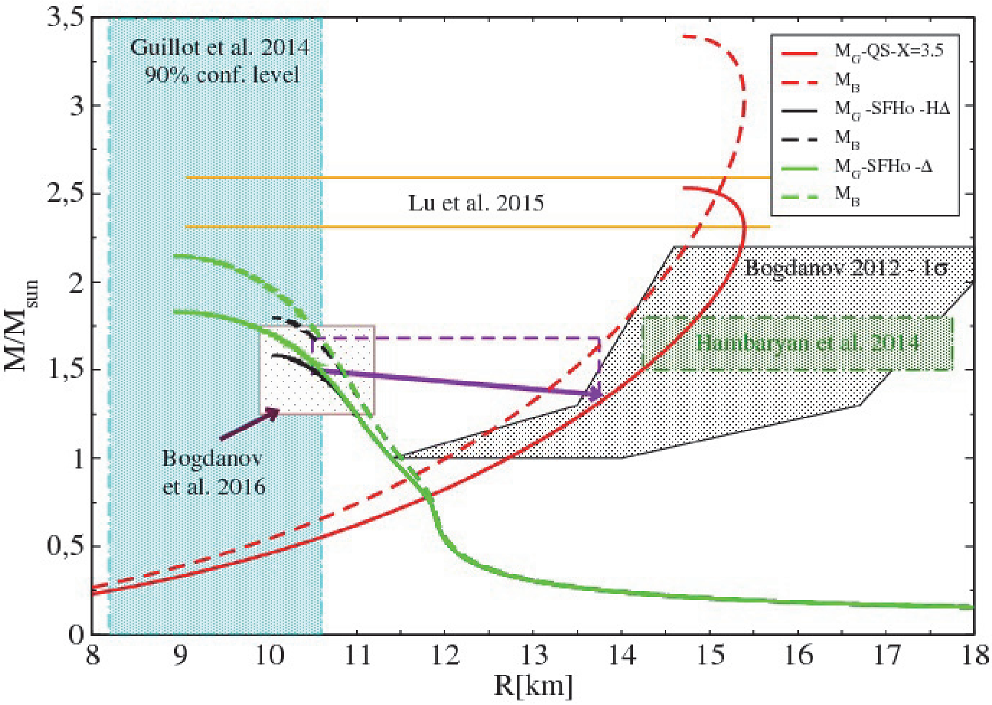

Fig1. *Equation of state for barionic matter (green) and strange quark matter (red). Masses of barions are marked with dashed lines and gravitational masses with continuous lines. A purple line shows an exemplary transition for a star which reached a limiting mass of 1.5 $M_{\odot}$. Figure from Wiktorowicz et al. (2017).*

In such a scheme, QSs in binary systems may form in three ways:

1. QS may form without any interaction,
2. one of the stars in a binary may at first form a NS and later, due to mass accretion, become a QS, or
3. a massive star may lost mass and instead of becoming a black hole, become a QS.

A very important aspect is the natal kick, which may disrupt a binary during supernova (SN) explosion. It is important only during the NS formation, as during the conversion into a QS, only the Blaauw kick (Blaauw, 1961), connected with the change of gravitational mass, is present. An exception is the situation when the post-SN mass of a NS is already above the threshold and a QS forms without additional mass accretion. Recent observations show that the binary fraction for massive stars (>10 $M_{\odot}$) is reaching nearly 100%. As QS may form only from such massive objects, probably all single Qss, if they exist, originate from disrupted binaries.

The natal kick is also extremely important for the formation of double QS, which are a probable source of strangelets. Two SNs can easily disrupt the binary, so a strong interactions between the stars are necessary in order to form a double QS. Indeed, W17 found a small amount of such objects for moderate metallicity only.

3. Modeling

In W17 a population synthesis study using the startrack code (Belczynski et al. 2002,2008) was performed. The aim of it was to investigate a population of QSs in different types of environments and see if it is possible to detect the existence of the two-families of compact objects in the coexistence zone.

For every model a population of 2 million binaries was simulated from the initial parameter space of X-ray binaries (see W17 for details). Calculations were performed with a use of Universe@Home distributed computing project.

4. Results

QSs may form as well in solar metallicity environment, as in 1% solar. The fraction of QSs never exceeds 5% of all compact objects with masses below 2.5 $M_{\odot}$. A significantly larger fraction, reaching 26% in some models, was observed in results for low-mass X-ray binaries (LMXB). Such accreting systems may efficiently increase mass of accreting NSs bringing them to the threshold for QS formation. It must be noted, however, that after the formation of a QS, a mass transfer may stop due to change in orbit resulting from the rapid change of gravitational mass of the accretor.

A typical route leading to the formation of a QS in a binary system is presented in Fig. 2. The initial parameters are similar to these for X-ray binary (XRB) progenitors. The primary is 7.2 $M_{\odot}$ on zero-age main-sequence (ZAMS), whereas the companion is about the solar mass. The primary evolves quicker and expands, fills its Roche lobe (RL), and commences a common envelope (CE) phase after about 50 Myr. The post-CE mass is too small to for a Nss, so a primary becomes a heavy white dwrf (WD; ~1.3 $M_{\odot}$). The secondary evolves longer but after about 5 Gyr being a RG fills its RL and starts a mass transfer (MT) onto a WD, which shortly after collapses to a NS. The companion refills the RL and restarts the MT. As only the NS reaches the deconfinement mass, it converts into a QS. A blaauw kick widens the orbit and typically no additional MT occurs.

Actually, most of the system (>90%) will be disrupted during the QS formation. It may be a consequence either of the NS formation, or the QS formation. A predicted formation rate of QSs in the Milky Way (MW) galaxy is between 11.6 and 23.9 per Myr. It is important to note the the general scheme of the QS formation is the same for all metallicities and two deconfinement masses.

In order to form a LMXB with a QS, i.e. system with a QS which accretes matter from the companion, the initial configuration needs to be different (Fig. 3). In such a case, the secondary is more massive (~4 $M_{\odot}$). As a result, the first MT from the secondary is unstable and leads to a second CE. Afterwards, a WD - helium star (HeS) system forms on a very short orbit of about 0.6 $R_{\odot}$. Companion fills the RL due to expansion on Helium MS and, after a phase of M, the WD forms a NS. HeS refills the RL and restarts the MT. After 20 Myr, the NS becomes a QS and the HeS becomes a WD. The orbit is short enough for the emission of gravitational waves to decrease the separation to the value in which a WD fills the RL. As a result, a MT onto a QS commences. We obtain a typical LMXB with a QS accretor.

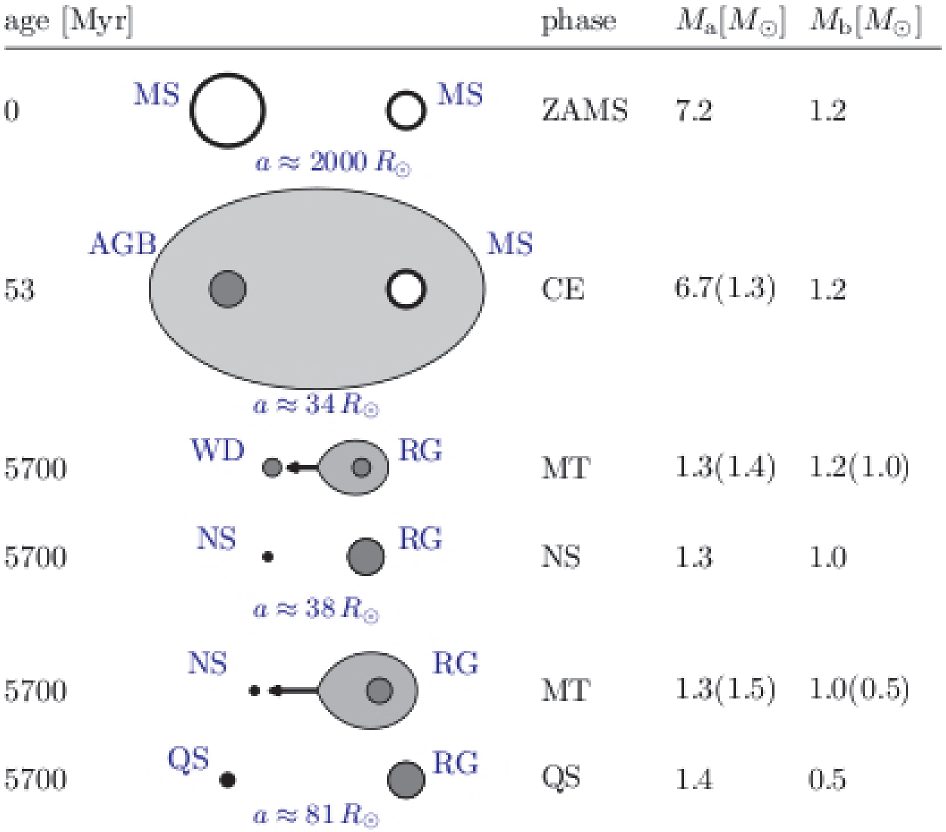

Fig2. *Typical binary evolution leading to the formation of a quark star. Abbreviations stay for: ZAMS – Zero Age Main Sequence; MS – Main Sequence; AGB – Asymptotic Giant Branch; CE – Common Envelope; WD – White Dwarf; RG – Red Giant; MT – Mass Transfer; NS – Neutron Star; QS – Quark Star. Time (left column) is provided in million years and masses (right columns) are provided in solar mass unit. See Sec. 3.2 for further details. Figure from Wiktorowicz et al. (2017).*

Despite some similarities, the formation route for QSs in LMXBs is different than the one for QSs in general. However, QSs in LMXBs are relatively more frequent than QSs in binaries in general. About 3-18% of QSs were found to reside in LMXBs according to the results of W17.

A very interesting result was presented in W17 for double QSs. Such systems may be formed only in moderate metallicity (10% $Z_\odot$) environment. What is more, the predicted merger rate for these objects is too small to trigger the strangelets pollution in the MW. It was estimated to be about 12 per Myr for the galaxy.

Typically, a double QS will form from a massive binary consisting of a 24 $M_\odot$ and 23 $M_\odot$ stars on ZAMS. The primary will evolve and expand while being on core Helium burning (CHeB) and start a MT. It will quickly lose the envelope and form a HeS. Shortly afterwards, the secondary expands on CHeB and fills its RL. However, this time the other star is to light and a CE occurs. As a result, the separation shrinks significantly. Afterwards, both stars undergo a SN and form directly QSs. The binding energy is high enough to keep the remnants bound. A typical time to merger is 8.6 Gyr.

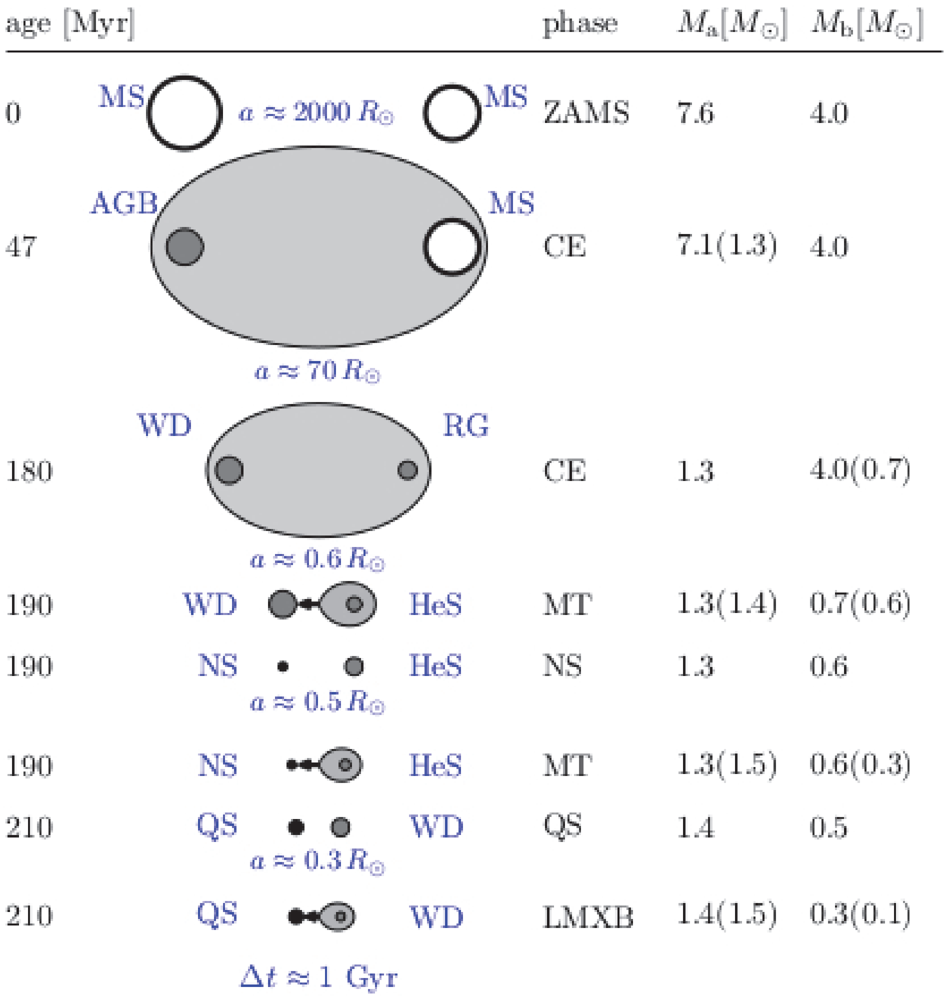

Fig3. *Typical evolution leading to the formation of a low-mass X-ray binary with a quark star accretor. The abbreviations and columns are as in Fig. 2 with additionally: LMXB – Low Mass X-ray Binary.*

5. Conclusion

A population synthesis is a very powerful tool for investigation of QSs in stellar systems. The most important results of Wiktorowicz et al. (2017) presented in this paper may be summarized as follows:

- Quark stars form typically through accretion onto a neutron stars.
- Most of quark stars are single, even though all of them probably originate from binary stars.
- Measurements of compact objects' masses are too few to reject or prove the two-families scenario.
- The rate of double quark star mergers in the Milky Way galaxy are too low to trigger deconfinement in all neutron stars.

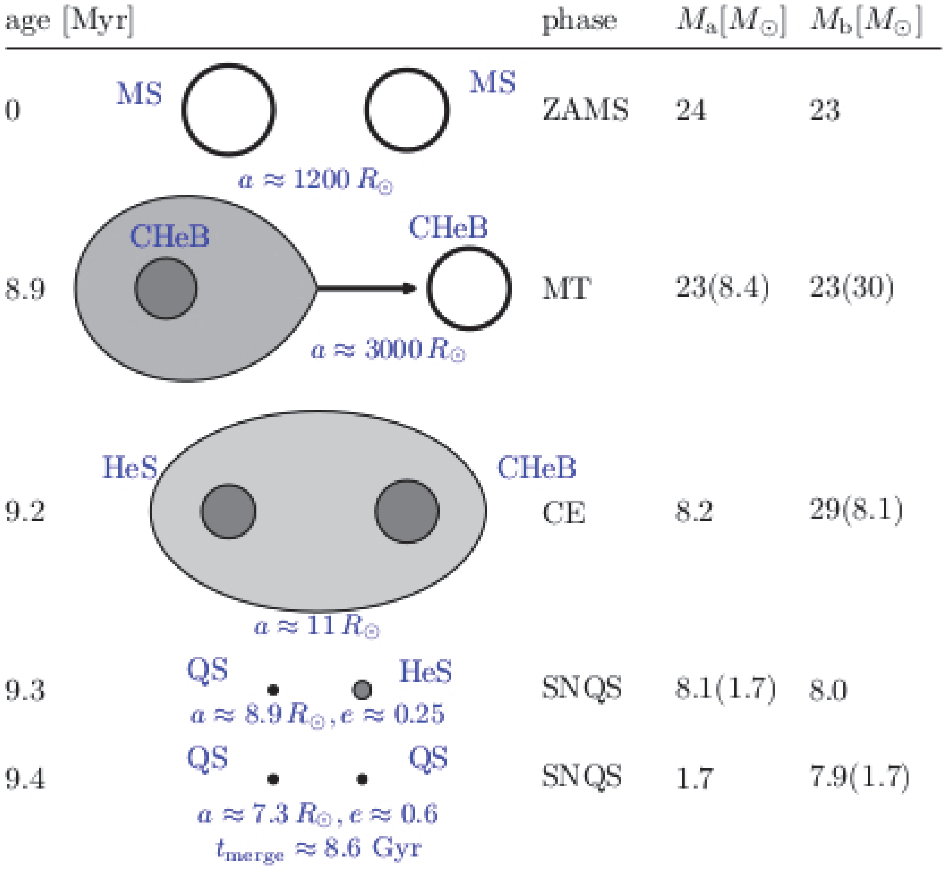

Fig4. *Typical evolution leading to the formation of a double quark star. The abbreviations and columns are as in Fig. 2 with additionally: CHeB – Core Helium Burning; HeS – Helium Star; SNQS – Quark Star formed directly in SuperNova explosion.*

References

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