Population synthesis of neutron stars, strange (quark) stars and black holes

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ABSTRACT

We compute and present the distribution in mass of single and binary neutron stars, strange stars, and black holes. The calculations were performed using a stellar population synthesis code. We follow evolution of massive single stars as well as binaries with high mass primaries. The final product of the latter evolution can be either a binary composed of a white dwarf and a compact object (neutron star, black hole, strange star), two compact objects in a binary, or two single stars if the system was disrupted. We find in binaries a population of black holes which are more massive than single black holes which are a product of either binary or single evolution. We also find that if quark stars exist at all, their population can be as large as the population of black holes.

Subject headings: binaries: close — stars: evolution, formation, neutron, strange (quark), black holes

1. INTRODUCTION

Binary population synthesis is a useful tool for studying the statistical properties of stars, including the compact objects (e.g., Pols \& Marinus 1994; Bethe \& Brown 1998; Portegies-Zwart \& Yungelson 1998; Bloom, Sigurdsson, \& Pols 1999; Belczynski \& Bulik 1999). Compact objects are stellar remnants of size much smaller than that of white dwarfs, so according to current views they could be either black holes or neutron stars or, possibly, quark stars.
We wish to address the following questions: What is the distribution of masses of the compact objects formed along different evolutionary paths? Given the distribution of compact object masses, what are the relative numbers of different types of objects (neutron stars, quark stars, black holes) both single and in binaries? What fraction of binaries give rise to single compact objects, and what fraction survives as binaries and of what type?

In Section 2 we shortly describe the population synthesis code used here, in Section 3 we summarize what is known about the masses of neutron stars, quark stars and of black holes. In Section 4 we discuss the constraints on the masses of compact objects, in Section 5 we present the results, and finally in Section 6 we give the conclusions.

2. POPULATION SYNTHESIS CODE

We use StarTrack, a stellar binary population synthesis code consisting of two parts. The single star evolution is based on the formulae from Hurley et al. (2000), modified as follows. We have changed the prescription for mass of the compact object formed in a supernova explosion. We use the original Hurley et al. (2000) formulae to obtain final CO core mass. We use models of Woosley (1986) to calculate the final FeNi core mass (for a given CO core mass), which will collapse and form a compact object during supernova explosion. Finally, we include calculations of Fryer and Kalogera (2001) to take into account black hole formation both through direct collapse and partial fall back.

The binary evolution is described in Belczynski, Kalogera & Bulik (2002) and Belczynski 2001. We evolve only binaries where at least one star will undergo a supernova explosion and form a compact object. The evolution starts at zero-age main sequence. During the course of evolution we include the following effects as appropriate: wind mass loss (standard, Wolf-Rayet, luminous blue variables), tidal circularization of binary orbit, conservative/nonconservative mass transfer, common envelope evolution, rejuvenation, hyper-accretion onto compact objects, detailed supernova explosion treatment.

Many binaries are disrupted in supernova explosions, as a result of mass loss and the natal kick. For supernova kicks we use the distribution presented by Cordes & Chernoff (1998). We use smaller kicks when the compact object is a black hole formed via partial fall-back, and no kicks for the black holes formed through direct collapse, for details see Belczynski et al. (2002). We continue to evolve each star, until the formation of a stellar remnant. At the endpoint of binary evolution either two single remnants are left or a binary - in either case at least one of the remnants is a compact object, while the other is either a compact object or a white dwarf.
3. QUARK STARS vs. NEUTRON STARS

Bodmer (1971) suggested that stars composed of up, down and strange quarks (in roughly equal numbers) may exist if quark plasma is the ground state of matter. Relativistic models of “strange” stars composed of such self-bound quark matter were first computed by Brecher & Caporaso (1976), Witten (1984), Alcock, Farhi & Olinto (1986), and Haensel, Zdunik & Schaeffer (1986). Alcock et al. (1986) give a detailed discussion of the possible avenues of formation of quark stars. If they are formed through a phase transition after a certain critical density is exceeded in the core of a neutron star, or if they are formed in a supernova of a star which has captured a “seed” of strange matter, quark stars could be more massive than neutron stars. In other scenarios, no neutron stars at all would exist, or the abundance of quark stars need not be a function of their mass. The astrophysics of quark stars has recently been reviewed by Cheng, Dai and Lu (1998) and Madsen (1999).

It has been argued that young, glitching, pulsars cannot be strange stars (Alpar 1987). Madsen (1988) and Caldwell & Friedman (1991) argue that strange stars in Hulse-Taylor type binaries would eventually contaminate the entire Galaxy with strange matter as a result of their binary coalescence, and thus preclude the formation of young neutron stars. But Kluźniak (1994) pointed out that many millisecond pulsars could in principle be strange stars, and Cheng & Dai (1996) suggest that strange stars could be formed through accretion induced phase transition in low-mass X-ray binaries (LMXBs). The compatibility of strange star models with the observed kHz QPOs frequencies in LMXBs was discussed by Bulik, Gondek-Rosińska & Kluźniak (1999), Zdunik et al. (2000) and others. Simulations of the hydrodynamics of coalescence indicate that quark matter is not always expelled in the binary merger of a strange star with another compact object (Lee, Kluźniak, & Nix 2001), so coexistence of neutron stars and strange stars may be possible, after all.

The existence of self-bound quark matter remains a hypothesis, and we cannot give definitive conclusions as to the abundance of quark stars. However, if one assumes that, say, quark stars constitute a fraction $f$ of compact objects in some mass range $(M_1, M_2)$ (and possibly a different fraction in some other mass range), then the number of quark stars can be read off from our plots of differential distributions. We will find, that if $f$ is a sizable fraction of unity, and if $(M_1, M_2)$ is not too narrow, then the number of quark stars may be comparable to the number of black holes.
4. Masses of Compact Objects

During the evolution we make nearly no distinction between the various types of compact objects, they only differ in mass (and in the natal kick distribution). In presenting the results, we assume that a compact object exceeding a certain mass is always a black hole. The actual value of the maximum mass of a neutron star is not known—the value of mass above which a stable neutron star can no longer exist depends on the unknown equation of state of matter at supernuclear densities. Models (Arnett & Bowers 1976, Kalogera and Baym 1996) give maximum masses from $1.4 M_\odot$ to above $2.9 M_\odot$. For the maximum masses of moderately rotating quark stars in the MIT bag model as a function of the unknown bag constant see Zdunik et al. (2000), and for the masses of quark stars when the Dey et al. (1998) equation of state is used, see Gondek-Rosińska et al. (2000). The maximum mass depends also on the rotation of the neutron star (Friedman, Parker & Ipser 1986; Cook, Shapiro & Teukolsky 1992). The corresponding increase of maximum mass in rapidly rotating quark stars is even larger (Stergioulas, Kluźniak & Bulik 1999). However, in this discussion we neglect these effects of stellar rotation, i.e., we assume none of the neutron stars (or quark stars) formed has a period less than $\sim 10$ ms.

Of course, there is no theoretical maximum to the mass of a black hole. The maximum masses we find in our calculations simply reflect the formation route of the black hole. We find that the most massive black holes survive in binaries (Fig. ??, compare panels labeled “group 0” or “group 1” with the ones labeled “group 2” or “group 3”).

Observations of binary stars yield direct information on masses of some compact objects. Neutron stars in the Hulse-Taylor type binaries have accurately measured masses of 1.44 and 1.39 $M_\odot$. Millisecond pulsars have been analyzed by Thorsett & Chakrabarty (1999) who found that they are consistent with all being in the narrow mass range of $1.34 \pm 0.04 M_\odot$. Among the neutron stars which exhibit X-ray bursts the mass of Cyg X-2 has been quoted as $1.78 \pm 0.23 M_\odot$ (Orosz & Kuulkers 1999). However, for most low mass x-ray binaries (LMXBs) the masses remain unknown.

There is a class of LMXBs where bright X-ray emission is transient and the masses of the compact object cluster in the range $\sim 5.5$ to $\sim 7.5 M_\odot$. These are thought to be black holes. At present our code does not yield an excess of black holes in this mass range with a white dwarf companion in the binary, instead a peak at about $10 M_\odot$ results (see Fig. ??). However, we note that according to our results, single black holes are particularly abundant at $M \sim 5 M_\odot$, and there is a deficit of single compact objects in the mass range of about $2.5 M_\odot$ to $5 M_\odot$. If the black hole LMXBs were formed through binary capture in globular clusters, our results would be consistent with the measured masses of the transient sources.
5. RESULTS

Compact objects may be formed both through single and binary stellar evolution. Single compact objects may be descendants of massive single stars but also of components of a binary system disrupted in a supernova explosion. We will denote the single compact objects formed from primordial single stars as group 0, and formed as a result of the binary evolution as group 1. Under favorable conditions some binaries survive supernova explosions, and they finally form tight systems with compact object/objects. Most of these binaries will consist of a white dwarf and a compact object and the rest will form binaries with two compact objects (we will denote the compact object in binaries with white dwarfs as group 2, and the double compact objects as group 3).

Figure ?? shows the number of compact objects per mass interval formed along each route. We start forming compact objects at mass $\sim 1.2M_\odot$ and their number falls off with the mass of the final compact object, as expected for our assumed initial mass function $\sim M^{-2.7}$. The peak in the distribution in Figure ?? around $\sim 10M_\odot$ reflects the relation we obtain between ZAMS mass of a progenitor and the final mass of a compact object. This relation for a wide range of progenitor ZAMS masses results in a final compact object mass of $\sim 10M_\odot$ (Belczynski et al. 2002). This is an effect of stellar wind which increases with the mass of the star, and thus decreases the final mass of a compact object for large initial stellar masses. As a result the mass of the FeNi core is a weak function of the initial mass of the star for a wide range of the ZAMS masses.

In Figure 2 we present, for each formation route separately, the cumulative fraction of compact objects as a function of their final mass. The normalization is such, that a fraction of unity corresponds to the total number of stars used in the simulation (we used a total of $7 \times 10^6$ binaries and $7 \times 10^6$ single stars), and assumed a binary fraction of 50%, i.e., we assumed that (initially) out of every three stars one is single and the other two are in a binary system. The single star and the primary mass in binaries was in the range 5 to $100M_\odot$, and the mass of the secondary was found assuming a flat mass ratio $q$ distribution and a $-2.7$ slope of the initial mass function. Each distribution rises quickly in the small mass range, which is also seen in Figure ???. Thus within each group even a small mass window $M_2 - M_1$ may yield a significant number of quark stars, if they constitute a sizable fraction of the objects in that mass window. For example, if quark stars are formed in the narrow mass range $(M_1, M_2)$, with $M_1 = 1.7M_\odot$ and $M_2 = 1.8M_\odot$, and no neutron stars of that mass exist, the fraction of quark stars in each group will be from a few to ten percent. This fraction is comparable to that of black holes in any given group, which is about $15-20\%$ in groups 0, 1, and 2, and $\approx 50\%$ in group 3. We also note that most of strange stars in the Galaxy should exist as single objects, and only a small fraction of them $\approx 10^{-5} - 10^{-4}$ is
going to be in double compact object binaries.

We have listed in Table 1 the numbers of binaries with compact object components obtained in our simulation. The binaries are classified according to their component masses, and for illustrative purpose we have labeled the objects in the mass range $1.7M_\odot < M < 2.5M_\odot$ as strange stars. The table allows to read the relative numbers of objects of different type.

6. DISCUSSION

We have shown the effects of the binary evolution on the distribution of masses of compact objects. As expected the bulk of the population of compact objects have masses below $2M_\odot$. While for single stellar evolution there exists a unique relation between the stellar mass and the compact object mass, there is no such relation when the binary evolution is taken into account. Binary evolution works both ways, the mass of a compact object formed from a particular star in a binary can be smaller or larger than that formed from an identical star undergoing single stellar evolution.

In the low mass range, the cumulative fraction of compact objects rises steeply with increasing mass—see Figure 2. Thus, even in a small mass interval $(M_1, M_2)$, the fraction of stars in the compact object population can be large. On the other hand the fraction of black holes hardly depends on their minimum mass (the cumulative curves flatten above $3M_\odot$). We conclude that the population of quark stars can easily be as large as the population of black holes, even if there is only a small mass window for their formation.

The low mass peak in differential distribution of Figure ??, is less pronounced for double compact object binaries, group 3. Thus a chance of finding quark stars in Hulse Taylor type objects is slim primarily because of the small number of such objects known so far. The prospects look better for compact objects in binaries with dwarfs. Although Thorsett & Chakrabaty (1999) show that the masses of these objects are consistent with being constrained to a narrow range, the mass function for individual objects allows different (higher or lower) masses. However the observed number of these sources is not large and the search here may suffer from small number statistics. Our results show that most quark stars should exist as single objects, yet it is the most difficult to measure the masses and radii for them. Therefore the search for quark stars may have to concentrate on single compact objects, such as pulsars.

It is interesting to note that the most massive black holes survive in binaries. This is related both to the difficulty of disrupting a binary with a very massive black hole and to
the need for fallback in forming such massive black holes with $M > 10M_\odot$.

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Table 1. Number of coalescing double compact objects obtained from $7 \times 10^6$ initial binaries

| Primary mass $[M_\odot]$ | WD$^a$ | NS$^b$ | SS$^c$ | BH$^d$ |
|---------------------------|-------|-------|-------|-------|
| $1.3 < M < 1.7$           | 32956 | 5533  |       |       |
| $1.7 < M < 2.5$           | 11305 | 4738  | 166   |       |
| $2.5 < M$                 | 9650  | 2216  | 1186  | 6291  |

$^a$white dwarf

$^b$compact object with mass $1.3 < M < 1.7$

$^c$compact object with mass $1.7 < M < 2.5$

$^d$compact object with mass $2.5 < M$
Fig. 1.— The number per unit mass of compact objects (i.e., of neutron stars, strange stars, or black holes) formed in various ways. The top left panel corresponds to the case of single stellar evolution (group 0), the top right panel represents the single compact objects formed in binary evolution (group 1), the bottom left panel shows the compact objects in white dwarf binaries (group 2), and the bottom right panel shows those compact objects whose binary companion is also a compact object (group 3).
Fig. 2.— The cumulative fraction of compact objects corresponding to the differential distributions of Figure ??.

The top curve is for compact objects arising from single stars. The remaining curves describe the outcome of binary evolution—note that the most likely fate of a compact object born in a binary is to be single, and that to end up as a companion to a white dwarf is more likely than to be in a binary with another compact object.