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Formation of massive skyrmion stars

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Abstract. We discuss different channels of formation of massive rapidly rotating neutron stars. We use a population synthesis code to estimate numbers of massive neutron stars in different evolutionary stages. For stiff equations of state the existence of neutron stars with masses $\gtrsim 2\,M_{\odot}$ is possible. An especially interesting situation occurs if the equation of state based on the Skyrme theory is realized in nature. A neutron star increases its mass by accretion from a secondary companion. Significant growth of a neutron star mass due to accretion is possible only for certain values of initial parameters of the binary. In this paper we show that a significant part of massive neutron stars with $M \gtrsim 2\,M_{\odot}$ can be observed as millisecond radio pulsars, as X-ray sources in pairs with white dwarfs, and as accreting neutron stars with very low magnetic fields.

Key words. stars: neutron – stars: evolution – stars: statistics – X-rays: binaries – binaries: close – pulsars: general

1. Introduction

Mass is one of the key parameters for neutron star (NS) physics and astrophysics. It can be measured with high precision in binary radio pulsar systems. Until very recently all estimates were obtained in a very narrow region 1.35–1.45 $M_{\odot}$ (Thorsett & Chakrabarty 1999). These values lie very close to the Chandrasekhar limit for white dwarfs. Thus, $M = 1.4\,M_{\odot}$ was considered to be standard value of the NS mass. Recently the range widened towards lower masses after the discovery of the double pulsar J0737-3039 (Burgay et al. 2003). One of the NSs in this system has $M = 1.25\,M_{\odot}$ (Lyne et al. 2004). The mass range also expanded towards higher masses, although this result is less certain. There is only one NS in a binary radio pulsar system with mass significantly higher than the canonical value 1.4 $M_{\odot}$. It is the pulsar J0751+1807 with the mass $2.1^{+0.4}_{-0.5}$ (95% confidence level) (Nice & Splaver 2004). All others are consistent with the standard mass value at the 1–2-σ level. However, the small number of massive radio pulsars can be a result of a selection effect(s).

There are reasons to suspect the existence of significant number of NSs with higher masses. Evidence comes both from theory and observations. Calculations of cooling curves of NSs suggest that some of these objects might be more massive than known sources in radio pulsar systems (see for example, Kaminker et al. 2001) with M up to 1.8 $M_{\odot}$ and probably more. Modeling of supernova (SN) explosions also suggest the existence of NSs with higher masses (Woosley et al. 2002). However, models of NS thermal history and SN explosions do not require masses $M \gtrsim 2\,M_{\odot}$, but there are observational indications of their existence.

Observationally, high masses of NSs are mainly supported by data on X-ray binaries (we do not discuss here data based on quasi-periodic oscillation measurements as they are model-dependent). Estimates for several systems give very high values: 1.8–2.4 $M_{\odot}$ for Vela X-1[1] (Quaintrell et al. 2003), 2.4 ± 0.27 $M_{\odot}$ for 4U 1700-37 (Clark et al. 2002; see also Heineke et al. 2003; van Kerkwijk 2004). Shahbaz et al. (2004) presented observations of a low-mass X-ray binary 2S 0921-630/V395 Car for which the 1-σ mass range for the compact object is 2–4.3 $M_{\odot}$. However, such measurements are not as precise as radio pulsar ones (for example, at the 3-σ level the mass of the NS in Vela X-1 is still compatible with the standard value).

The existence of NSs with $M \sim 2$–$2.4\,M_{\odot}$ is not in contradiction with the present day theory of NS interiors. There are several models with stiff equation of state (EOS) which allow the existence of NSs with masses $\gtrsim 2\,M_{\odot}$ (see a review and references in Haensel 2003). Here we will focus on the so-called *skyrmion stars* (SkyS) as they are expected to be NSs with the highest value of maximum mass ($M_{\max}$).

In 1999 Ouyed and Butler discussed an EOS based on the model of Skyrme (1962). A NS with such EOS has $M_{\max} = 2.95\,M_{\odot}$ even for a non-rotating configuration. Usually maximum rotation can increase the limit by ∼15–20%. Rapidly rotating SkyS were discussed by Ouyed (2002, 2004), and for

[1] This range is based on the two estimates given in Quaintrell et al. (2003): 1.88 ± 0.13 and 2.27 ± 0.17 $M_{\odot}$.

this case $M_{\max} = 3.45\ M_{\odot}$ and $R = 23$ km (this model also has relatively large radii of the NS). Such a model is very interesting from the astrophysical point of view, and it is important to discuss scenarios of formation of compact objects with such high masses. Our goal in this work is to identify evolutionary tracks of binary systems which can lead to the formation of NSs with high masses, and to discuss the possible observational appearence of such systems and their relative and absolute numbers in the Galaxy. As we do not explicitly use any EOS in our calculations, our results can be applied to other stiff equation of state and even to low-mass black holes (BHs).

In the next section we discuss evolutionary paths at the end of which a massive NS can be formed. We then give an estimate of the number of massive NSs in the Galaxy. Finally we discuss our results and propose systems which are more favorable to host massive NSs.

2. Possible channels of massive neutron star formation

As mass determination for NSs is possible only in binary systems[2] we focus on potentially observable stages of evolution of binary systems in which a massive NS can form. Below we discuss possible ways of massive NS formation.

Since we are mostly interested in compact objects with rapid rotation (because they can have higher maximum masses) it is necessary to follow evolution in a binary as such objects cannot form from single stars (Heger et al. 2003). Thus, it is necessary to study the evolution of close binary systems. Except for evolutionary tracks which lead to a formation of a massive NS in a binary, we follow paths at the end of which an isolated massive NS can form. The appearence of a rapidly rotating single massive NS due to binary evolution can be result of a coalescence of two compact objects (NSs or white dwarfs – WDs), or a result of a slower merging process in which a normal star is involved, or the result of the evaporation of a low-mass secondary companion by an active pulsar. At some stages during its evolution a binary which is going to produce an object of interest to us can be observed as an X-ray source, which is why it is important to select evolutionary paths for them also.

The main result of the collapse of cores of massive stars are NSs with $M \sim 1.2$–$1.5\ M_{\odot}$. This conclusion is supported both observationally (van Kerkwijk 2004) and theoretically (Timmes et al. 1996; Fryer & Kalogera 2001; Woosley et al. 2002). Numerical models of collapse are not as precise as necessary to determine the exact shape of a NS mass spectrum (for example the amount of fallback is not well known), however, calculations show that the formation of NSs with high masses is not favourable and most of them should have $M \sim 1.3$–$1.4\ M_{\odot}$.

Discovery of a NS with $M \gtrsim 1.8\ M_{\odot}$ would mean that the mass increased after formation of the compact object during its evolution (if the mass is significantly higher than $1.8\ M_{\odot}$ then such a conclusion seems to be inevitable). Based on this proposition we call below NSs with $M > 1.8\ M_{\odot}$ as *massive*.

A NS can increase its mass due to fallback, coalescence with another NS, or accretion from a secondary companion. As we note above, the first way is not well studied, and we do not discuss it further. Coalescence of NSs is well understood (see Rosswog et al. 2003, and references therein). The rate of NS coalescence in the Galaxy is about 1 per 10^4 yrs. As a result a rapidly rotating massive isolated NS (or a BH) can form. This evolution also will not be discussed further. In the following only binary evolution of a NS in a pair with a normal star or a WD will be studied.

We initially assume an isotropic collapse, i.e. zero kick. Such an assumption is not realistic as most NSs – nearly all radio pulsars – obtain at birth high additional velocity ~100–1000 km s^{-1} (Arzoumanian et al. 2002). However, it is much easier to understand the main processes in binary evolution if one neglects this. In addition, if a binary was not unbounded after a SN explosion then the orbital eccentricity quickly decays after the secondary fills its Roche lobe. So, we are not interested in the question of binary survival then it is possible to neglect kick to simplify the explanation.

We start with a qualitative discussion (below in Sect. 2.1 a more detailed consideration is given). The most obvious channel to form a rapidly rotating massive NS is evolution in a low-mass or intermediate mass binary (see, for example, recent calculations by Podsiadlowski et al. 2002). This path includes, for example, millisecond pulsars (however it is not the only possible output).

As we are interested here in systems with a high mass ratio (a massive primary produces a NS and the secondary star has low mass) it is necessary to consider three different situations after NS formation when the secondary fills its Roche lobe: i) a normal star can fill its Roche lobe without common envelope formation; ii) a normal star can fill its Roche lobe with common envelope formation; iii) a WD fills its Roche lobe.

To fill the Roche lobe a normal secondary star has to evolve further than the main sequence stage. During its evolution prior to the Roche lobe overflow the mass of the star is nearly constant (see detailed tracks below). A common envelope is not formed if the normal star is not significantly heavier than the NS. In this regime, mass is not lost from the binary system. For more massive secondaries, formation of a common envelope is inevitable, mass transfer is unstable. In this regime, a significant fraction of the mass flow is lost from the system, so the mass of the NS grows less effectively. It is only partly compensated by the higher mass of the donor.

After the common envelope stage the orbital separation becomes smaller, so later on even a degenerate core of the secondary – a WD – can fill the Roche lobe.

2.1. Evolutionary tracks

For our calculations we use the "Scenario Machine" code developed at the Sternberg Astronomical Institute[3]. A description of most of the parameters of the code can be found in

[2] In principle one can determine an isolated NS mass by microlensing effects, however, we do not investigate this issue here.

[3] `http://xray.sai.msu.ru/sciwork/scenario.html` and `http://xray.sai.msu.ru/~mystery/articles/review/`

Lipunov et al. (1996). Below we mention those which are the most important for us here:

- all NSs are born with $M = 1.4\,M_{\odot}$;
- at the common envelope stage a hypercritical accretion (with $\dot{M}$ much larger than the Eddington value) is possible;
- during accretion the magnetic field of a NS decays to a value that cannot prevent rapid (maximum) rotation of the NS;
- the Oppenheimer-Volkoff mass of a rapidly rotating NS (the critical mass of a BH formation) is assumed to be $3.45\,M_{\odot}$ according to Ouyed (2004).

For zero kicks we distinguish two groups of tracks which produce massive NSs. A typical track from the first group has an initial value of the semimajor axis $a = 290\,R_{\odot}$ and star masses $M_1 = 10.5\,M_{\odot}$, $M_2 = 2\,M_{\odot}$ (Fig. 1 left)[4]. After the massive component leaves the main sequence it expands and fills its Roche lobe. As a result the common envelope stage begins. During this stage the orbit shrinks by more than an order of magnitude, and the primary loses about 3/4 of its mass and becomes a low-mass helium SN progenitor. After the SN explosion the orbit has low eccentricity and $a \sim 7$–$8\,R_{\odot}$. The mass of the secondary is not changed during these stages of evolution.

Until the secondary fills its Roche lobe the NS is at the stages of *ejector* and *propeller* (see for example Lipunov 1992, for stage descriptions). During these stages the magnetic field is assumed to be constant. Stage durations can be found in Lipunov et al. (1996)[5].

After the secondary fills the Roche lobe the NS starts to accrete. At that moment the mass ratio is about 0.7 (the NS is lighter) and a mass transfer is stable with nearly zero mass loss from the system. Up to equalizing of component masses, matter transfer goes on a thermal time scale and after equalizing – on a nuclear. The process of accretion can be stopped because of a switching on of a millisecond radio pulsar. This happens when the donor's mass is $\sim 0.1\,M_{\odot}$. The remnant of the secondary companion then can be evaporated completely; while the evaporation is proceeding the systems looks like the famous "Black widow" pulsar 1957+20 (and its twin PSR J2051-0827). If accretion is not stopped then it continues until a planet-like (Jupiter mass) companion remains. As we see the final stage of such an evolution is a "single" massive rapidly rotating NS. In both cases the final mass of a NS can reach 3.2–3.3 $M_{\odot}$. We can observe such a system at the stage of accretion which lasts 90% of the evolution. Masses of NSs in these accreting systems can be in the range from the initial mass (1.4 $M_{\odot}$ in our case) up to 3.2–3.3 $M_{\odot}$. Orbits can be relatively wide.

The described evolutionary channel appears to be narrow in the sense that small changes in the initial conditions do not allow massive NS formation. Also, uncertain parameters of the common envelope stage can significantly influence this path.

Ranges of initial parameters of evolutionary tracks from the second group are given in Table 1. We give maximal and minimal values for two types of tracks (2a and 2b) which differ in the final stages of evolution. The orbital period, $P_{\rm orb}$, is given in Table 1 for illustration. In our calculations we use masses and semimajor axes. The values of $P_{\rm orb}$ given in the table are calculated using maximum masses and minimum semimajor axes for the shortest period, and minimum masses and maximum axes for the longest period. Thus, ranges for $P_{\rm orb}$ for tracks 2a and 2b intersect.

Table 1. Parameters for tracks from the second group.

Parameter	Min	Max	Width
Track 2a			
a	279 $R_{\odot}$	670 $R_{\odot}$	0.20
M_1	10.3 $M_{\odot}$	12.8 $M_{\odot}$	0.054
M_2	3.9 $M_{\odot}$	6.7 $M_{\odot}$	0.13
$P_{\rm orb}$ $^{(*)}$	$123^{\rm d}$	$537^{\rm d}$	
Track 2b			
a	135 $R_{\odot}$	279 $R_{\odot}$	0.17
M_1	10.3 $M_{\odot}$	12.4 $M_{\odot}$	0.046
M_2	3.9 $M_{\odot}$	7.4 $M_{\odot}$	0.15
$P_{\rm orb}$ $^{(*)}$	$41^{\rm d}$	$144^{\rm d}$	

$^{(*)}$ $P_{\rm orb}$ is given just as an illustration, see the text.

A typical representative of the 2a subgroup has the following initial parameters: $a = 300\,R_{\odot}$, $M_1 = 12\,M_{\odot}$, $M_2 = 4\,M_{\odot}$. The main difference from the first group of tracks is a more massive secondary companion. Because of that, the common envelope during the first mass transfer is less effective, and after a SN a system with $a = 170\,R_{\odot}$ and low eccentricity is formed (the mass of the secondary is not changed). Later the secondary fills the Roche lobe. The mass ratio is high, mass transfer is unstable and a common envelope forms. At the end of the common envelope stage the secondary becomes a WD with $M \sim 0.8\,M_{\odot}$, and the orbital separation diminishes to $5\,R_{\odot}$. During the common envelope stage the NS increases its mass up to $\sim 2.3\,M_{\odot}$ (for more massive donors mass loss from the system is more effective, so in such cases the NS mass can be lower: $\sim 1.9\,M_{\odot}$).

After the formation of a binary consisting of a NS and a WD the evolution in the second group can take one of two different paths. For some tracks (2a) from the second group the time of approaching of the components due to gravitational wave emission is too long, so there is no Roche lobe overflow. Systems with smaller orbital separation have enough time to approach each other close enough for the beginning of WD overflow. This situation corresponds to the initial parameters $a = 200\,R_{\odot}$, $M_1 = 12\,M_{\odot}$, $M_2 = 4\,M_{\odot}$ (track 2b in Table 1).

The main difference between tracks 2a and 2b is smaller orbital separation in the latter case. Track 2b is similar to the one on the right panel of Fig. 1, but after the common envelope, the semiaxis of the system is just $\sim 3\,R_{\odot}$. A WD has enough time to fill the Roche lobe and completely transfer its mass to the NS. At the end we have a single rapidly rotating NS. The NS mass for this case is increased to $\sim 3\,M_{\odot}$. Stages with a WD are shown in the box as they distinguish the track 2b from 2a.

[4] A high resolution figure is available at:
http://xray.sai.msu.ru/~polar/html/publications/ouyed/

[5] The subsonic propeller stage is not taken into account as for binaries with big accretion rates it is very short.

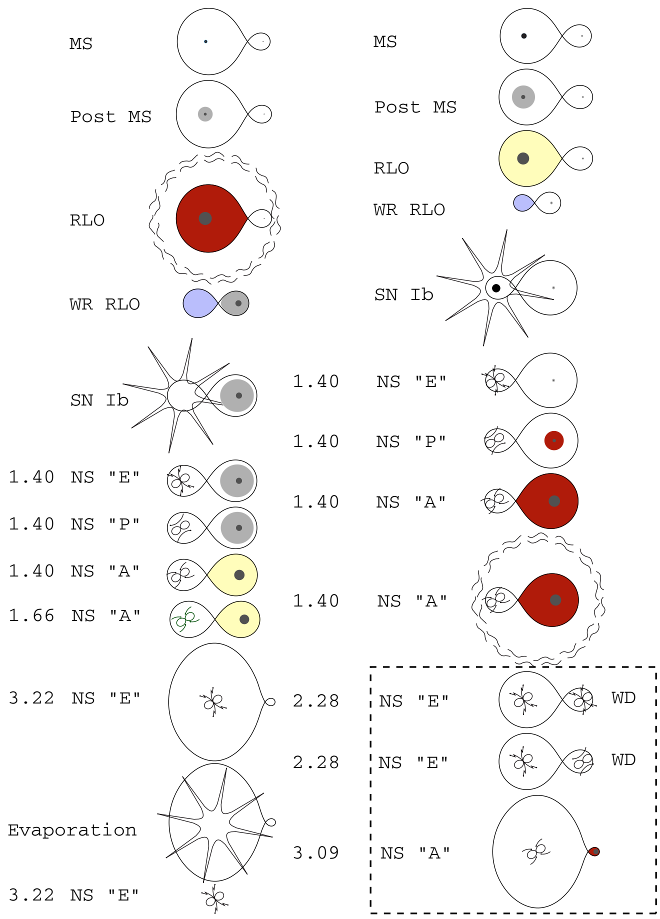

Fig. 1. Evolutionary tracks for massive NS formation. *In the left panel* we show a typical track from the first group. The first mass transfer (from the primary) results in a common envelope formation due to the high mass ratio. Accretion onto a NS from the secondary companion proceeds stably without a common envelope. *In the right panel* we show an evolutionary path of a system from the second group. This track differs with the higher mass of the secondary companion. Because of this difference the first mass transfer goes on without a common envelope. A NS gathers additional mass during one or two episodes of accretion. If the orbital separation is not very large (~200 $R_{\odot}$, see text) then at first the NS accretes from a normal secondary filling its Roche lobe, and then from a WD (this stage is shown in the dashed frame). For wider systems the evolution stops after the mass transfer from the normal secondary star (i.e. before the frame). On the left of each track we indicate evolutionary stage (in the notation from Lipunov et al. 1996) and NS masses.

When a semimajor axis is larger than $a \sim 670\,R_{\odot}$ the second common envelope results in NS–star merging, so a Thorne-Zytkow object is formed. Its evolutionary path is not very clear. Formation of massive NS and a formation of a BH are both possible. We do not include this possibility into our calculation.

2.2. Evolutionary tracks with kicks

Above we discuss two families of tracks with zero kicks which result in massive NS formation. However, it is necessary to include kicks as they are a general property of NS formation. A kick can change the orbital parameters after a SN explosion, it can even make the system unbounded. If after a SN (and after a brief period of circularization of an orbit) we obtain in our calculations a system with parameters in the range that was obtained above for the zero kick, then the following history of the system should be the same as described in Sect. 2.1.

The additional velocity which a NS obtains at birth can change the range of initial parameters that are necessary for massive NS formation. It is especially important to estimate if ranges for M_1, M_2 and a are changed significantly or not. As the kick velocity and NS mass in our calculations are assumed to be independent of the mass of an exploding star (see below Sect. 4.1) we do not expect that the range of masses of primaries should be modified. The same can be said about the range of initial masses of secondaries because these stars do not suffer any important evolutionary changes before a SN expolsion. Since a kick can dramatically change the orbital parameters the situation is different for the initial orbital separation range. For example, with a kick, systems wider than the ones discussed in Sect. 2.1 can still form massive NSs.

In the next section we present results of our calculations of the population synthesis of massive NSs for both scenarios.

3. Estimate of observable number of massive neutron stars in the Galaxy

To estimate the number of massive NSs in the Milky Way we run several sets of population synthesis calculations for the ranges of initial parameters which correspond to the two groups of tracks described above. Each run includes calculations of 10^6 individual binary evolutionary tracks.

We run the model for zero kick velocities and for non-zero ones. For the latter case we use the distribution similar to the one suggested in Arzoumanian et al. (2002). We use a bimodal distribution with equal fraction of objects in each mode. The average velocity in the first mode is 175 km s $^{-1}$ and in the second is 750 km s $^{-1}$, the distribution in each mode is Maxwellian.

For the scenario without kick we proceed as follows. For the second group of tracks we used ranges indicated in Table 1. The width given in the table is calculated as $0.5(\max - \min)/(\max + \min)$. For the first family of tracks we used the range for a from 230 to 346 $R_{\odot}$, for M_1 from 8.4 to 12.6 $M_{\odot}$, and for M_2 from 1.6 to 2.4 $M_{\odot}$.

For the scenario which takes into account the additional velocity gained by a NS at birth we used a wider range of initial semimajor axis: from 200 to 2000 $R_{\odot}$. Masses are chosen in the same way as for the zero kick variant.

The results of the calculations for non-zero kick are the following (we assume the total number of all NSs in the Galaxy as 10^9, and the galactic age as 1.5×10^{10} yrs). In the first channel (Fig. 1 left panel) we do not obtain a significant number of massive NSs. Most of these objects are formed in the second channel. The formation rate of massive NSs was found to be 6.7×10^{-7} yrs^{-1}. This corresponds to ~10 000 of these compact stars in the Galaxy. For zero kick the formation rate is larger, 4×10^{-6} yrs^{-1}, so the total number is ~60 000.

Certainly only a fraction of massive NSs at any given moment passes through stages that are observable, i.e. the

Table 2. Fractions of massive NSs at different stages.

Stage	With kick	Without kick
Ejector	0.32	0.39
Propeller + Georotator	0.02	0.08
Accretor	0.66	0.53
Hypercritical stages	5×10^{-6}	0

accretor stage and the radio pulsar stage. Some of these objects are at *ejector* and *propeller or georotator* stages. None of them are favourable for detection[6]. In Table 2 we give fractions of massive NSs at each stage. It is clear that *accretors* are more numerous (but the number of massive NSs at the stage of superEddington accretion is negligible).

For the non-zero kick model about 25% of accreting massive NSs have normal stars as secondaries, the rest have WD companions. For zero kick nearly all massive NSs accrete from WDs that fill their Roche lobes.

Mass distributions for both scenarios are shown in Fig. 2. Note that the small details in the figure are due to statistical noise (for example, the first peak on the rising part of the dashed curve, or the middle peak on the solid one). The only important details are the two peaks at $M \sim 2.3\,M_{\odot}$ and $M \sim 3.1\,M_{\odot}$, which correspond to tracks 2a and 2b (see the right panel of Fig. 1 and Table 1). As we found only two groups of tracks which lead to the formation of massive NS only the results obtained for these groups are shown. All contributions from other types of tracks are not considered here and in Fig. 3.

Finally, in the last figure we represent luminosity distributions. For the scenario with non-zero kick about 1/2 of the massive NSs have $M > 2.5\,M_{\odot}$. Thus, we can conclude that in the Galaxy there are several thousand accreting massive NSs with luminosities $10^{34} \lesssim L \lesssim 10^{36}$ erg s^{-1}.

4. Discussion and additional comments

Here we give some uncertainties of the scenario. Then we briefly discuss the possibility of massive NS formation in globular clusters, low-mass BHs, and types of sources which can host massive NSs.

4.1. Correlations between initial parameters of neutron stars

The scenario of binary evolution that we use has different types of uncertainties. Here we look at possible correlations between parameters of the scenario.

In our calculations we assumed that such initial parameters of NSs as spin period, magnetic field, mass and velocity are uncorrelated with each other. The reason for this assumption is trivial: there is no direct indication of such correlations. However, theorists have suggested a plethora of them. We give a list (probably incomplete) of possibilities and corresponding references to original papers.

- Spin – magnetic field (Thompson & Duncan 1993).
- Magnetic field – mass (Popov et al. 2002; Heger et al. 2004).
- Internal structure – velocity (Bombaci & Popov 2004).
- Binarity – velocity (Podsiadlowski et al. 2004).
- Core mass – velocity (Scheck et al. 2004).

As here we mainly speak about masses and kick velocities, let us briefly comment on the last two items. Our calculations may not be strongly influenced by such correlations. The reason is that the mass added during accretion is much larger then the difference in initial masses, i.e., as we need to accrete nearly two solar masses to obtain the most massive SkyS at maximum rotation, we can safely forget about the range of initial masses.

[6] The *ejector* stage does not coincide with the radio pulsar stage, but includes it as a substage. So here we are speaking about non-detectability of *ejectors* that are not active as radio pulsars. See for example Lipunov (1992) or Lipunov et al. (1996) for more details.

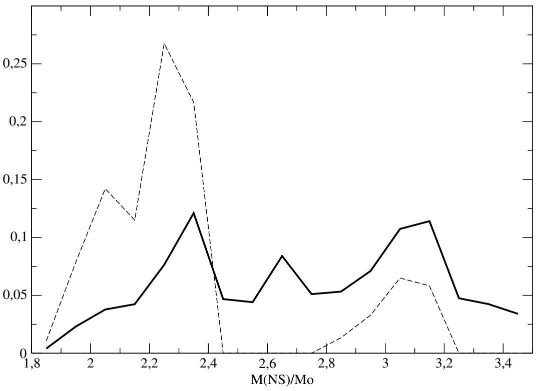

Fig. 2. Mass distribution of NSs. As we are interested only in the massive population we do not show the results for compact objects with $M < 1.8\,M_{\odot}$. The upper mass limit corresponds to SkyS with maximum rotation (Ouyed 2004). The dashed line represents results for the scenario with zero kick. The solid line is the non-zero kick. Left peaks for both distributions correspond to NSs with a single episode of accretion. Right peaks are formed by NSs which also increased their masses via accretion from WDs. Distributions were normalized to unity, i.e. the area below each line is equal to one.

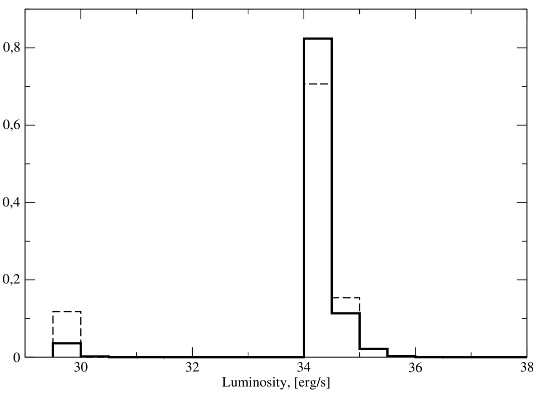

Fig. 3. Luminosity distribution of accreting massive NSs. The left bin includes all sources with $L < 10^{30}$ erg s^{-1}. The dashed line corresponds to the scenario with zero kick. The solid line – non-zero kick. In the ranges $10^{30} \lesssim L \lesssim 10^{34}$ erg s^{-1} and $10^{36} \lesssim L \lesssim 10^{37}$ erg s^{-1} the number of systems is not equal to zero, however, it is very small. All distributions are normalized to unity.

That is why in our calculations we even assume that all NSs have the same initial mass. For the same reason we can neglect the second item in the list above.

As here we deal with systems with high accretion rates, and the magnetic field is assumed to decay due to accretion, the first item also is not very important for us. Even if a NS was a magnetar in its early years, later, after field decay, it can follow a normal evolutionary path.

We do not discuss here the possibility of phase transition in NS interiors. Formation of a quark phase due to mass increase can significantly influence the subsequent history of a binary system, but we neglect it here as in that case formation of massive NSs is impossible.

4.2. Globular clusters

All evolutionary tracks that we present above correspond to binary evolution in the Galaxy, and so they cannot be directly applied to globular clusters. However, we are mainly interested in systems which after formation of a NS appear to be stiff, i.e. orbital velocities in binaries are larger than the velocity dispersion in a cluster. It is also true during the subsequent evolution of a system, and it can be violated only at the stage of Roche lobe overflow by a WD. We can conclude that the dynamical influence of the globular cluster stellar population should not destroy the systems under discussion. Still, duration of various evolutionary stages can be different in clusters and in the galactic disc, and so our estimates of relative fractions cannot be valid for globular clusters.

It is possible to speculate that as the formation rate of millisecond pulsars is enhanced in globular clusters, the formation rate of massive NSs can also be higher there than in the disc of the Galaxy. It is an important question because massive NSs from globular clusters can enrich the disc population of these objects (so, our calculations which neglect this contribution give a lower limit on the number of massive NSs in the Galaxy). In our opinion millisecond radio pulsars and X-ray sources in globular clusters can be good candidates for a search for massive NSs.

4.3. Low-mass black holes

As was described in the Introduction, at present all well-determined values of NS masses lie below $\sim 1.5\,M_\odot$. On the other hand most of BH mass determinations lie around values 6–10 $M_\odot$ (Ziolkowski 2004), so there is an indication of a gap in the intermediate mass range. Accretion cannot fill this gap if, as it is standardly assumed, NSs are formed with $M \lesssim 2\,M_\odot$ and BHs are formed with $M \gtrsim 5\,M_\odot$.

If an EOS of NSs with a very high $M_{\rm max}$ is realized in nature, then up to $\sim 3\,M_\odot$ or even further, in the case of maximum rotation, we can find NSs. Otherwise the gap above $\sim 2\,M_\odot$ should be populated only by BHs. Even in the case of the EOS discussed by Ouyed & Butler (1999), low-mass BHs can form from rapidly-rotating massive NSs as they slow down.

Figure 2 (the solid line) clearly shows that the number of low-mass BHs (or any other type of compact objects) with $M \gtrsim 3.2$ in our scenario is small. However, if $M_{\rm max}$ is $\sim 2\,M_\odot$, and if a binary is not significantly influenced during BH formation (i.e. accretion continues), then the number of BHs with $M_{\rm max} \lesssim M \lesssim 3.2\,M_\odot$ is non-negligible[7].

There are several examples of binary systems with an estimate of the mass of the compact object $\sim$3–4 $M_\odot$ (Orosz et al. 2004; Shahbaz et al. 2004). These objects are considered as BH candidates. In principle such objects can be formed in the framework of the scenario discussed above after the mass of a NS exceeds the Oppenheimer-Volkoff limit.

4.4. Possible candidates

The main astrophysical manifestations of massive NSs are the same as for normal NSs: X-ray sources and radio pulsars. However, there are differences. Very massive NSs should have short spin periods as they get an additional mass by accretion which spins them up and provoke magnetic field decay[8]. Of course a given millisecond pulsar can contain a NS with normal mass. The presence of a low-mass degenerate companion (a WD) can be an indication that the system can hide a massive NS. An additional signature of a massive NS is very low magnetic field.

If the magnetic field is very small, then the Alfven radius becomes less than the NS radius, and the accretion disk can nearly approach the NS surface. This situation takes place when

$$B \lesssim 2\times 10^9\ {\rm G}\,\dot M_{-8}^{1/2} m^{1/4} r_{10}^{-5/4}\,,$$

here $\dot M_{-8} \equiv \dot M/10^{-8}\,M_\odot/{\rm yr}$, $r_{10} \equiv r_{\rm NS}/10$ km and m is the mass of the NS in Solar units. Thus, the magnetic field strength can be $\lesssim 10^9$ G for an Eddington accretion rate. In that case the formation of a boundary layer is favorable, and in the NS spectrum an additional thermal component can be present (Inogamov & Sunyaev 1999). For massive NSs including the Ouyed EOS, the radius of the star is smaller than the distance to the last stable orbit, so the disc cannot actually smoothly approach the surface, but the qualitative properties of a spectrum will remain the same.

All these consideration can be summarized in a list of types of objects that can contain massive NSs.

- X-ray sources with weak pulsations with signatures of a boundary layer;
- millisecond X-ray pulsars with WD companions;
- millisecond radio pulsars with WD companions;
- other kinds of millisecond X-ray pulsars;
- other kinds of millisecond radio pulsars.

By "other kinds" we mean millisecond pulsars with other types of companions or isolated (but old) ones. We do not include in our calculations secondary companions with very low initial mass (brown dwarfs). However, such systems cannot produce

[7] Mass growth of NSs and BHs in close binaries is also discussed in Bogomazov et al. (2005) and in Bogomazov et al. (in preparation).

[8] If a NS has a very short spin period then pulsations in an X-ray source can be undetectable, as is observed for many low-mass X-ray binaries.

massive rapidly-rotating SkyS as the total amount of accreted matter is not sufficient. NSs with very low-mass companions like the millisecond accreting pulsar SAX J1808.4-3658 or like "black widow"-like radio pulsars can be produced in our scenario via evaporating degenerate or non-degenerate secondaries (see discussions on the evolution of this source in Ergma & Antipova 1999; Bildsten & Chakrabarty 2001, and references therein).

Unfortunately our calculations cannot provide exact numbers of objects of each type. Uncertainties are connected with the influence of a population of sources from globular clusters and with uncertainties of the scenario itself. For example we do not take into account the influence of rotation on the evolution of normal stars (see Langer et al. 2003).

Ouyed (2002, 2004) discussed three binary systems as possible candidates for massive SkyS: 4U 0614+09, 4U 1636-53, 4U 1820-30. From the point of view of the evolutionary scenarios discussed above all three could contain a massive NS. 4U 1820-30 is especially interesting. The orbital period of the system is only 11 min which means that the secondary is a low-mass helium star (see Ballantyne & Strohmayer 2004, and references therein). However, this source is situated in a globular cluster, and so our considerations should be applied with care.

5. Conclusions

We discussed possible channels of massive NS formation. If the EOS based on the Skyrme model suggested by Ouyed & Butler (1999) is realized in nature then these objects can be SkyS with masses up to 3.45 $M_\odot$ for maximum rotation. The estimated numbers of these sources in the Galaxy is high enough. The most likely candidates are X-ray binaries with WDs as donors, millisecond radio pulsars in pairs with WDs and accreting NSs with very low estimated magnetic field. If no such massive NSs are found in these systems then the SkyS EOS has to be rejected.

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References

Arzoumanian, Z., Chernoff, D. F., & Cordes, J. M. 2002, ApJ, 568, 289
Ballantyne, D. R., & Strohmayer, T. E. 2004, ApJ, 602, L105
Bildsten, L., & Chakrabarty, D. 2001, ApJ, 557, 292
Bogomazov, A. I., Abubekerov, M. K., Lipunov, V. M., & Cherepashchuk, A. M. 2005, Astron. Rep., 49, in press
Bombaci, I., & Popov, S. B. 2004, A&A, 424, 627
Burgay, M., D'Amico, N., Possenti, A., et al. 2003, Nature, 426, 531
Clark, J. S., Goodwin, S. P., Crowther, P. A., et al. 2002, A&A, 392, 909
Ergma, E., & Antipova, J. 1999, A&A, 343, L45
Fryer, C. L., & Kalogera, V. 2001, ApJ, 554, 548
Haensel, P. 2003, in Final Stages of Stellar Evolution, ed. C. Motch, & J.-M. Hameury, EAS Publications Series, 7, 249
Heger, A., Woosley, S. E., Langer, N., & Spruit, H. C. 2003, in Stellar evolution, ed. A. Maeder, & P. Eenes (San Francisco: ASP), Proc. of IAU Symp., 215, in press [arXiv:astro-ph/0301374]
Heger, A., Woosley, S. E., & Spruit, H. 2004, ApJ, submitted [arXiv:astro-ph/0409422]
Heinke, C. O., Grindlay, J. E., Lloyd, D. A., & Edmonds, P. D. 2003, ApJ, 588, 452
Hobbs, G., Faulkner, A., Stairs, I. H., et al. 2004, MNRAS, 352, 1439
Inogamov, N. A., & Sunyaev, R. A. 1999, Astron. Lett., 25, 269
Langer, N., Yoon, S.-C., Petrovic, J., & Heger, A. 2003, in Stellar Rotation, ed. A. Maeder, & P. Eenes (San Francisco: ASP), Proc. of IAU Symp., 215, in press [arXiv:astro-ph/0302232]
Lipunov, V. M. 1992, Astrophysics of neutron stars (Berlin: Springer-Verlag)
Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. 1996, Astrophys. Space Sci. Rev., 9, 1
Lyne, A., Burgay, M., Kramer, M., et al. 2004, Science, 303, 1153
Nice, D. J., & Splaver, E. M. 2004 [arXiv:astro-ph/0411207]
Orosz, J. A., McClintock, J. E., Remillard, R. A., & Corbel, S. 2004 [arXiv:astro-ph/0404343]
Ouyed, R. 2002, A&A, 382, 939
Ouyed, R. 2004 [arXiv:astro-ph/0402122]
Ouyed, R., & Butler, M. 1999, ApJ, 522, 453
Podsiadlowski, Ph., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107
Podsiadlowski, Ph., Langer, N., Poelarends, A. J. T., et al. 2004, ApJ, 612, 1044
Popov, S. B., Prokhorov, M. E., Colpi, M., Treves, A., & Turolla, R. 2002, in Proc. of the Third International Sakharov Conference on Physics, ed. A. Semikhatov, et al. (Moscow: Scientific World), 420 [arXiv:astro-ph/0210688]
Quaintrell, H., Norton, A. J., Ash, T. D. C., et al. 2003, A&A, 401, 313
Rosswog, S., Ramirez-Ruiz, E., & Davies, M. B. 2003, MNRAS, 345, 1077
Shahbaz, T., Casares, J., Watson, C., et al. 2004 [arXiv:astro-ph/0409752]
Shakura, N. I., & Sunyaev, R. A. 1987, Adv. Space Res., 8, 135
Scheck, L., Plewa, T., Janka, H.-Th., Kifonidis, K., & Müller, E. 2004, PRL, 92, 1103
Skyrme, T. H. R. 1962, Proc. R. Soc. London A, 260, 127
Thompson, C., & Duncan, R. C. 1993, ApJ, 408, 194
Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1996, ApJ, 457, 834
van Kerkwijk, M. H. 2004 [arXiv:astro-ph/0403489]
Woosley, S. E., Heger, A., & Weaver, T. A. 2002, Rev. Mod. Phys., 74, 1015
Kaminker, A. D., Haensel, P., & Yakovlev, D. G. 2001, A&A, 373, L17
Ziolkowski, J. 2004, Chin. J. Astron. Astrophys., in press [arXiv:astro-ph/0404052]