Astronomy & Astrophysics manuscript no.
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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. For stiff equations of state an existence of neutron stars with masses $\gtrsim 2\,M_\odot$ is possible. Especially interesting possibility is opened if the equation of state based on the Skyrme theory is realized in nature. This equation of state was proposed recently by Ouyed and Butler. We use a population synthesis code to estimate numbers of massive neutron stars on different evolutionary stages. 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 particular values of initial parameters of the binary. In this paper we show that significant part of massive neutron stars with $M \gtrsim 2\,M_\odot$ can be observed as millisecond radio pulsars, as X-ray sources in pair with white dwarfs, and as accreting neutron stars with very low magnetic fields.

Key words. stars: neutron – stars: evolution – stars: statistics – stars: binary – X-ray: stars

1. Introduction

Mass is one of the key parameter for neutron star (NS) physics and astrophysics. It can be measured with high precision in binary radio pulsar systems. Up to very recent time obtained results fall in a very narrow region 1.35-1.45 $M_\odot$ (Thorsett & Chakrabarty 1999). This value lies very close to the Chandrasekhar limit, and so for years $M = 1.4\,M_\odot$ was considered to be a standard value of a NS mass. Recently the range widened towards lower masses thanks to 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). There are no known NSs in binary radio pulsar systems with masses significantly higher than the canonical value $1.4\,M_\odot$. However, this can be a result of a selection effect(s).

There are reasons to suspect an existence of NSs with higher masses. Evidence for such a proposal comes both from theory and observations. Calculations of cooling curves of NSs suggest that some of these objects should be more massive than known sources in radio pulsar systems (see for example, Kaminker, Haensel & Yakovlev 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, Heger & Weaver 2002). Still models of NS thermal history and SN explosions do not requier masses $M \gtrsim 2\,M_\odot$, but there are observational indications for their existence.

Observationally high masses of NSs are supported by data on X-ray binaries. Estimates for several systems give very high values: **1.8-2.4 $M_\odot$ for Vela X-1**[1] (Quaitrell 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). Very recently Shahbaz et al. (2004) presented observations of a low-mass X-ray binary 2S 0921-630/V395 Car for which 1-σ mass range for the compact object is 2-4.3 $M_\odot$. Still it is necessary to note that such measurement are not as precise as the 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 an existence of NSs with masses $\gtrsim 2\,M_\odot$ (see a review and references in Haensel 2003). Here we will focus on so called *skyrmion stars* (SkyS) as they are expected to be a kind of NSs with the highest value of maximum mass ($M_{\rm max}$).

In 1999 Ouyed and Butler discussed an EOS based on the model of Skyrme (1962). A NS with such EOS has $M_{\rm max}$=2.95 $M_\odot$ even for non-rotating configuration. Usualy maximum rotation can increase the limit by $\sim$ 15-20%. Rapidly rotating SkyS were discussed by Ouyed (2002, 2004), and for this case $M_{\rm max}$=3.45 $M_\odot$ and $R =$

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

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23 km (this model also has relatively large radii of NSs). Such 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 note is to pick out evolutionary tracks of binary systems which can lead to the formation of NSs with high masses, and to discuss possible observational appearences of such systems and their relative and absolute numbers in the Galaxy. As we do not use explicitly any EOS in our calculations, then 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. Then we 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 masses) it is necessary to follow evolution in a binary as such objects cannot form from single stars (Heger et al. 2003), so its necessary to study evolution of close binary systems. Except evolutionary tracks which lead to a formation of a massive NS in a binary we follow the paths at the end of which an isolated massive NS can form. An appearence of a rapidly rotating single massive NS due to a binary evolution can be a result of a coalescence of two compact objects (NSs or white dwarfs — WDs), or a result of a more slowly merging process in which a normal star is involved, or a result of an evaporation of a low-mass secondary companion by active pulsar. At some stages during its evolution a binary which is going to produce finally an object of our interest can be observed as an X-ray source, that is why it is important to select evolutionary paths also for them.

The main output of a 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, Frayer & Kalogera 2001, Woosley, Heger & Weaver 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 $M \sim 1.3$-$1.4\,M_\odot$.

[2] Note, that in principle there is a possibility to determine an isolated NS mass by microlensing effects, however we do not touch this issue here.

A discovery of a NS with $M \gtrsim 1.8\,M_\odot$ should mean that the mass was 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 as *massive* NSs with $M > 1.8\,M_\odot$.

A NS can increase its mass due to fallback, coalescence with another NS or accretion from the secondary companion. As we note above the first way is not well studied, and we do not discuss it below. Oppositely coalescence of NSs is well understood (see Rosswog et al. 2003 and references therein). The rate of NSs 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 way of evolution also will not be discussed below. In the following only binary evolution of a NS in pair with a normal star or a WD will be studied.

At first for an illustration let us assume an isotropic collapse, ie. zero kick. Such an assumption is not realistic as most part of NS – nearly all radio pulsars – obtain high additional velocity ($\sim$100–1000 km s^{-1}) at birth (Arzoumanian, Chernoff & Cordes 2002). However it is much easier to understand main processes in a binary evolution if one neglects kick. In addition, if a binary was not unbounded after a SN explosion then an orbital eccentricity quickly decays after the secondary fills its Roche lobe. So, if we are not interested at the moment in the question of the binary survival then it is possible to neglect kick to simplify the explanation.

Let us start with a qualitative discussion (below in sec. 2.1 a more detailed consideration is given). The most obvious channel to form a rapidly rotating massive NS is an 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 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 the NS formation when the secondary fills its Roche lobe: *i.)* a normal star can fill its Roche lobe without a common envelope formation; *ii.)* a normal star can fill its Roche lobe with a common envelope formation; *iii.)* a WD fills its Roche lobe.

To fill the Roche lobe a normal secondary star has to evolve further 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 significant fraction of the mass flow is lost from the system, so the mass of the NS grows less effectively. Which is only partly compensated by higher mass of the donor.

After the common envelope stage orbital separation becomes smaller, so later on even a degenerated 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 in the Sternberg Astronomical Institute. [3] Description of most of parameters of the code can be found in Lipunov, Postnov & Prokhorov (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 down to the value which cannot prevent rapid (maximum) rotation of the NS.
- 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 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 sets on. During this stage the orbit shrinks by more than an order of magnitude, and the primary looses about 3/4 of its mass and becomes a low-mass helium SN progenitor. After the SN explosion the orbit has low eccentricity and $a \sim 7$–$8\ R_\odot$. Mass of the secondary is not changed during these stages of the evolution.

Till the secondary fills its Roche lobe the NS is at the stages of *ejector* and *propeller* (see for example Lipunov 1992 for stages descriptions). **During these stages the magnetic field is assumed to be constant. Stage durations can be found in Lipunov, Postnov & Prokhorov (1996).** [5] After the secondary fills the Roche lobe the NS starts to accrete. At that moment mass ratio is about 0.7 (the NS is lighter) and mass transfer is stable with nearly zero mass loss from the system. Up to equalizing of components masses matter transfer goes on a thermal time scale, after equalizing – on a nuclear. Process of accretion can be stopped because of a switching on of a millisecond radio pulsar. It 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 till 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 a sense that small changes in the initial conditions do not allow a massive NS formation. Also uncertain parameters of the common envelope stage can significantly influence this path.

The range of initial parameters of evolutionary tracks from the second group are given in the table 1. We give maximal and minimal values for two types of tracks (2a and 2b) which differes by the final stages of evolution. **The orbital period, $P_{\rm orb}$, is given in the table 1 just for an illustration. In our calculations we use masses and semimajor axes. So the values of $P_{\rm orb}$ given in the table are simply calculated using maximum masses and minimum semimajor axes for the shortest period, and, oppositely, minimum masses and maximum axes for the longest period. Due to that ranges for $P_{\rm orb}$ for tracks 2a and 2b intersect.**

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 form 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. Mass ratio is high, mass transfer is unstable and the 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 down 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 rapprochement of the components due to gravitational wave emission is too long, so that there is no Roche lobe overflow. Systems with smaller orbital separation have enough time to approach to 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 the 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 semiaxis of the system is just $\sim 3\,R_\odot$.

[3] Online materials are available at http://xray.sai.msu.ru/sciwork/scenario.html and http://xray.sai.msu.ru/ ~mystery/articles/review/.

[4] Colored version of the figure in high resolution is avalable on the Web: 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.

Table 1. Parameters for tracks from the second group

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

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

A 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 up to $\sim 3\,M_\odot$. This track is shown in the right panel of fig. 1. Stages with a WD are shown in the box as they distinguish the track 2b from 2a.

For semimajor axis $a > 670\,R_\odot$ the second common envelope results in NS-star merging, so the Thorne-Zytkow object is formed. Its evolutionary path is not very clear. A formation of a 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 NSs formation. However, it is necessary to include kicks as they are a general property of a NS formation. A kick can change 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 which was obtained above for a zero kick, then the following history of the system should be the same as described in sec. 2.1.

Additional velocity which a NS obtains at birth can change the range of initial parameters that are necessary for a massive NS formation. Especially it is important to estimate if ranges for M_1, M_2 and a are changed significantly or not. As a kick velocity and a NS mass in our calculations are assumed to be independent on a mass of an exploding star we do not expect that a 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 then the ones discussed in sec. 2.1 can still form massive NSs.

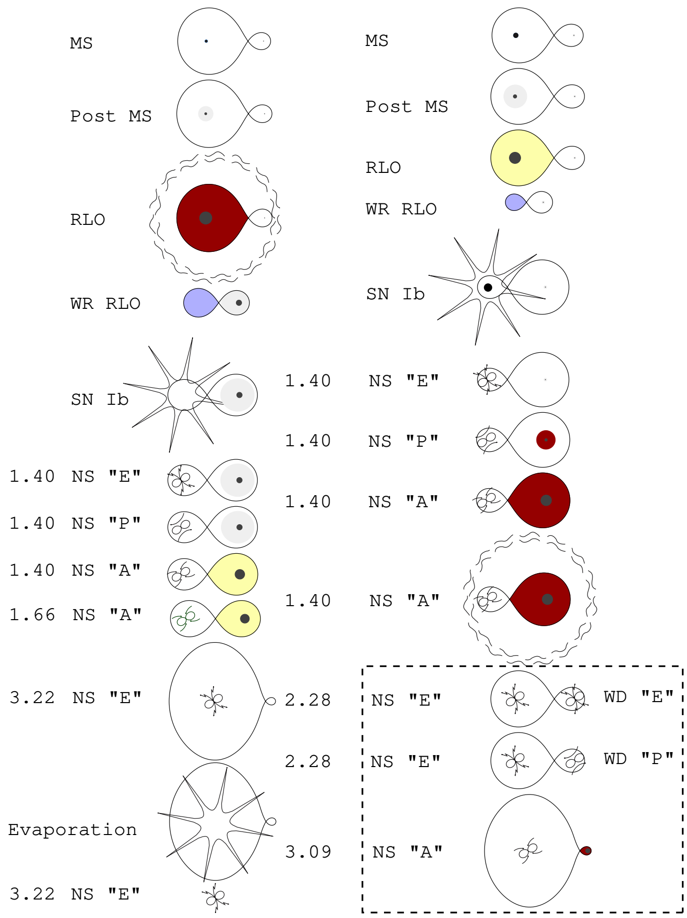

Fig. 1. Evolutionary tracks for massive NS formation. In the left panel we show a typical track from the first group. The first mass transfer (from the primary) results in a common envelope formation due to high mass ratio. Accretion onto a NS from the secondary companion proceeds stably without a common envelope. In the right panel we show an evolutionary path of a system from the second group. This track differs by a higher mass of a secondary companion. Because of this difference the first mass transfer goes on without a common envelope. A NS gathers an additional mass during one or two episodes of accretion. If the orbital separation is not very large ($\sim 200\,R_\odot$, 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 (ie. before the frame). On the left from each track we indicate evolutionary stage (in notation from Lipunov, Postnov & Prokhorov 1996) and NS masses. In the frame we also indicate WD evolutionary stages.

In the next section we present results of our calculations of 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 calculation for the ranges of initial parameters which correspond to 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	$5 \cdot 10^{-6}$	0

two groups of tracks described above. Each run includ calculation of 10^6 individual binary evolutionary tracks

We run the model for zero kick velocities and for no: zero ones. For the latter case we use the distribution sir ilar to the one suggested in Arzoumanian, Chernoff Cordes (2002). We use bimodal distribution with equ fraction of objects in each mode. An average velocity the first mode is 175 km s $^{-1}$ and in the second it is 7! km s $^{-1}$, 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 the table 1. 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 an additional velocity gained by a NS at birth we used 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 significant number of massive NSs. Most of these objects are formed in the second channel. Formation rate of massive NSs was found to be $6.7\,10^{-7}$ yrs^{-1}, what corresponds to $\sim 10\,000$ 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 $\sim 60\,000$.

Certainly only a fraction of massive NSs at any given moment passes through stages which are observable, ie. the *accretor* stage and the stage of radio pulsar. Some of these objects are at stages of *ejector* and *propeller or georotator*. All three of them are not favourable for detection[6]. In the table 2 we give fractions of massive NSs on 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 75% have WD companions. For zero kick nearly all massive NSs accrete from WDs which fill their Roche lobes.

Mass distributions for both scenarios are shown in the fig. 2. **Note, that all 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 which corresponds to tracks 2a and 2b (see the right panel of Fig. 1 and table 1).**

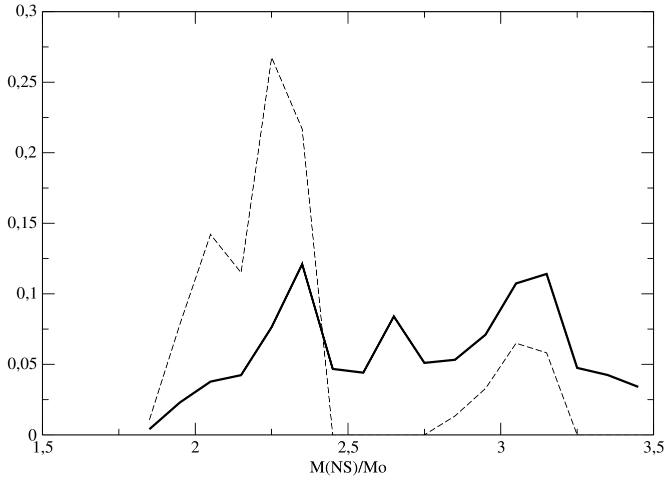

Fig. 2. Mass distribution of NSs. As we are interested only in the massive population we do not show the results for compact objects with $M < 1.8\,M_\odot$. Upper mass limit corresponds to SkyS with maximum rotation (Ouyed 2004). The dashed line represents results for the scenario with zero kick. The solid line – 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. Distribution were normalized to unity, ie. an area below each line is equal to one.

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

4. Discussion and additional comments

Here at first we notice some uncertainties of the scenario. Then we briefly discuss a 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 we used has different types of uncertainties. Here we touch just on of them – possible correlations between parameters of the scenario.

We assume that such parameters of NSs as inital spin period, magnetic field, mass, velocity are uncorrelated with each other. The reason for this assumption is trivial: there is no direct indication on such correlations. However, theorists suggested

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

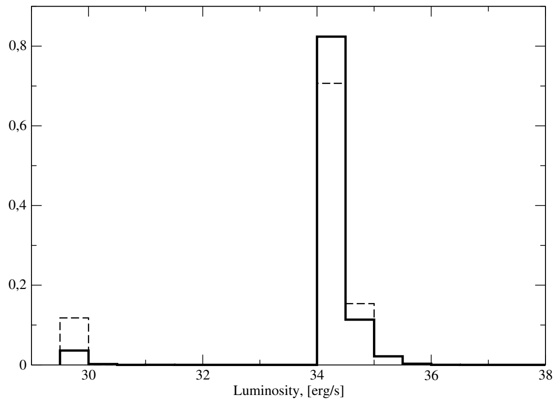

Fig. 3. Luminosity distribution of accreting massive NSs. The left bin includes all sources with $L < 10^{30}$ erg s^{-1}. The dashed line corresponds to the scenario with zero kick. The solid line – non-zero kick. In the ranges $10^{30} \lesssim L \lesssim 10^{34}$ erg s^{-1} and $10^{36} \lesssim L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

plethora of of them. We just give a list (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 make a short comment on 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. That's 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.

4.2. Globular clusters

All evolutionary tracks that we present above correspond to binary evolution in the Galaxy, and they cannot be directly applied to globular clusters. However, we are mainly interested in systems which after a formation of a NS appear to be stiff, ie. orbital velocities in binaries are larger than a velocity dispersion in a cluster. It is also true during the following evolution of a system, and it can be violated only at the stage of Roche lobe overflow by a WD. We can conclude that a dynamical influence of the globular cluster stellar population should not destroy 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 then the formation rate of massive NSs can also be higher 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. In our opinion millisecond radio pulsars and X-ray sources in globular clusters can be good candidates for a search of massive NSs.

4.3. Low-mass black holes

As it 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 on a gap in intermediate mass range. **Briefly we can say, that 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 $\sim 2M_\odot$ should be filled 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.

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

There are several examples of binary systems with an estimate of a mass of a 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 frame of the scenario discussed above after mass of a NS exceeds the Oppenheimer-Volkoff limit.

4.4. Possible candidates

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

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

have short spin periods as they get an additional mass by accretion which spin-up them and provoke magnetic field decay. [8] Of course a given millisecond pulsar can contain a NS with a normal mass. Presence of a low-mass degenerated companion (a WD) can be an indication that the system can hide a massive NS. One can mention another additional signature of a massive NS – 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

$$B \lesssim 2 \cdot 10^9 \ \mathrm{G}\dot{M}_{-8}^{1/2} m^{1/4} r_{10}^{-5/4} ,$$

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

All these consideration can be summarized in a list of types of objects which 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. Note, that we do not include into our calculations secondary companions with very low initial mass (brown dwarfs). However, such systems cannot produce 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 degenerated or non-degenerated 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 influence of population of sources from globular clusters and with uncertainties of the scenario itself. For example we absolutely do not take into account influence of rotation on the evolution of normal stars (see Langer et al. 2003).

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

Ouyed (2002, 2004) discussed three binary systems as possible candidates to massive SkyS: 4U 0614+09, 4U 1636-53, 4U 1820-30. From the point of view of evolutionary scenarios discussed above all three really can contain a massive NS. 4U 1820-30 is especially interesting. The orbital period of the system is only 11 minutes which means that the secondary is a low-mass helium star (see Ballantyne & Strohmayer 2004 and references therein). However this sources 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. Most favourable candidates are X-ray binaries with WDs as donors, millisecond radio pulsars in pair with WDs and accreting NSs with very low estimated magnetic field. If no of so massive NSs are found in these systems then the SkyS EOS has to be rejected.

Acknowledgements. We thank drs. I. Bombaci, R. Ouyed, and the unknown referee for comments on the text of the manuscript. SP thanks prof. J. Zdunik for discussions on the EOS. This work was supported by the RFBR grants 04-02-16720 and 03-02-16068.

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