Magnetars origin and progenitors with enhanced rotation

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ABSTRACT

Among a dozen known magnetar-candidates there are no binary objects. As an estimate of a fraction of binary neutron stars is about 3-10\% it is reasonable to address the question of solitariness of magnetars, to estimate theoretically the fraction of binary objects among them, and to mark out the most probable companions. We present population synthesis calculations of binary systems. In this study we assume the hypothesis that magnetic field of a magnetar is generated at the protoneutron star stage due to dynamo mechanism, so rapid rotation of the core of a progenitor star is essential. Our goal is to estimate the number of neutron stars originated from progenitors with enhanced rotation. In our calculations the fraction of neutron stars originated from such progenitors is about 8-9\%. This should be considered as an upper limit to the fraction of magnetars as some of progenitors can lose momentum. Most of these objects are isolated due to coalescences of components prior to a neutron star formation, or due to a system disruption after the second supernova explosion. The fraction of such neutron stars in survived binaries is about 1\% or lower. Their most numerous companions are black holes.

Key words: stars: neutron – stars: evolution – stars: statistics – binaries: close – X-ray: binaries – magnetic fields

1 INTRODUCTION

There are more than 10 anomalous X-ray pulsars (AXPs) and soft gamma repeaters (SGRs) in our Galaxy known at the moment (Woods, Thompson 2004). The standard model of AXPs...
and SGRs involves highly magnetized neutron stars – magnetars (Thompson, Duncan 1993). All these sources are isolated, i.e. no binary components were reported (we can add also radio pulsars with large magnetic fields, all of them are single objects too). Population synthesis studies suggest that from few up to $\sim 10\%$ of neutron stars (NSs) are expected to have companions (see, for example, Iben, Tutukov (1996) and calculations below). This number depends on the kick velocity distribution and on the fraction of binaries in the whole stellar population. Probably, now it is reasonable to start a discussion ”Why all known magnetars are isolated?”.

Immediately two possibilities arise:

- **Large kick velocities.** It was suggested that magnetars have large kicks. This option naturally explains the solitarity of magnetars: if a progenitor star was a member of a binary then anyway in most cases the system should be disrupted. So, if all magnetars are born with very large recoil velocities then they have to be isolated.

- **Particular evolutionary paths.** Magnetars seldom can have companions even for standard kicks. This can happen if magnetars are mainly born from single stars, or if due to some properties of evolution nearly all progenitor binaries are disrupted prior or immediately after a magnetar formation.

The first option is quite possible and widely discussed (see, for example, Wheeler et al. (2000) and references therein). However, let us focus here on the second possibility connected with evolution in a binary as actually there is no direct evidence for large kicks of magnetars. In particular, we start with a hypothesis that magnetars are born only from stars with enhanced rotation, and then we discuss evolutionary paths that produce such stars.

Thompson, Duncan (1993) and Thompson, Murray (2001) demonstrate that for the generation of a magnetar-scale magnetic field rapid rotation of a newborn NS is absolutely necessary. Rotation of massive stars is now actively studied in connection with gamma-ray bursts (GRBs) (Heger et al. 2003; Langer et al. 2003; Thompson, Chang, Quataert 2004; Fryer, Heger 2005). Heger et al. (2003) suggest that isolated stars do not produce cores with the rate of rotation sufficient to launch a GRB. In this sense it is reasonable to expect that GRBs are formed in binaries. This topic was discussed, for example, by Langer et al. (2003). These authors show that primary (i.e. initially more massive) components loose angular mo-

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1 We do not discuss here alternatives to the magnetar scenario, see, for example, Menou, Perna, Hernquist (2001).
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Momentum via a stellar wind; only secondary components of massive binaries produce cores with rapid rotation.

In the case of a NS formation Heger et al. (2003) show that rapid rotation can be reached if no additional loss of angular momentum (suggested by Spruit (2002)) occur. However, inclusion of such losses significantly decreases spins of stellar cores. Probably, in this case an additional enhancement of rotation is necessary. As in the case of GRB progenitors extra-momentum can be gained in course of binary evolution. Without detailed calculations it is possible to point at two possibilities: coalescence of binary components and spin-up of a secondary component via Roche lobe overflow. In the latter case systems like Be/X-ray binaries can be considered as an example of progenitors of magnetars. Most probably such systems are unbounded after the second supernova (SN) explosion. It can be a natural explanation for solitary nature of magnetars. Possibly in rare cases a magnetar can have as a component a NS or a black hole (BH). If coalescences are the main producers of progenitors of magnetars then the resulting compact objects are single by definition. Still, a primary component also can gain angular momentum due to synchronization of its spin with orbital rotation if the mass transfer is accompanied by a common envelope formation and if the separation between two components significantly decreases.

Obviously, a detailed population synthesis of close binaries is necessary to determine the fraction of stars with significant angular momentum at a pre-SN stage. In the following section we present such calculations.

2 CALCULATIONS AND RESULTS

In this short note we use the “Scenario Machine” code for binary population synthesis (Lipunov, Postnov, Prokhorov 1996) to calculate the number of NSs born from progenitors with enhanced rotation. The code is developed at the Sternberg Astronomical Institute since early 80s. Initially it was mainly designed to calculate evolution of massive binaries. The main feature is the detailed calculation of magneto-rotational evolution of NSs. During more than 20 years the code was applied to many problems of binary evolution. Topics studied before 1996 (including detailed studies of coalescence rate of binary NSs and black

2 Online material is available at http://xray.sai.msu.ru/sciwork/scenario.html and http://xray.sai.msu.ru/~mystery/articles/review/. The first link is to the web-demonstrator of the program, only single track calculations are available. The second URL is for the online version of Lipunov, Postnov, Prokhorov 1996.

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holes) are summarized in (Lipunov, Postnov, Prokhorov 1996). In the last 10 years the code was also used to study evolution of SN rates, populations of binaries after bursts of star formation, population of binary radio pulsars with massive companions, Be/X-ray systems, and evolution of binaries in globular clusters.

Among all possible evolutionary paths that end in formation of a NS we select those that lead to angular momentum increase of a progenitor. These paths include:

- Coalescence prior to a NS formation.
- Roche lobe overflow by a primary (it spins-up the secondary companion).
- Roche lobe overflow by a primary with a common envelope (it spins-up the primary if there is enough time for synchronization).
- Roche lobe overflow by a secondary without a common envelope formation prior to an explosion of a primary (it spins-up a primary).
- Roche lobe overflow by a secondary with a common envelope (it spins-up the secondary if there is enough time for synchronization).

Below we dub NSs originated through these paths as “magnetars” (of course, if they really have strong magnetic fields should be a subject of a separate detailed study, so here it is just a hypothesis; also we neglect a possibility of significant angular momentum losses after rotation has been enhanced by some processes).

The question of synchronization needs few additional comments. We consider that the synchronization is possible if for a survived binary the duration of the stage which follows the common envelope one is twice longer than $T_{\text{sync}}$ (see, for example, Shore (1994) p. 49):

$$T_{\text{sync}} = 3500 \left[ \frac{(1 + q)}{q} \right] \left( \frac{L}{L_\odot} \right)^{-1/4} \times$$

$$\left( \frac{M}{M_\odot} \right)^{1.25} \left( \frac{R}{R_\odot} \right)^{-3} \left( \frac{P_{\text{orb}}}{\text{days}} \right)^{2.75} \text{yrs}.$$  

Potentially, if a primary had transferred a significant angular momentum onto a secondary, but later on the secondary, in its turn, filled its Roche lobe and started to transfer momentum back, then the secondary’s rotation is reduced. Such tracks appear in our calculations. We save for analysis tracks for which a secondary component forms a common envelope and synchronizes with orbital rotation. We exclude tracks for which a secondary only filled its Roche lobe (ie. no synchronization) and transferred angular momentum to the primary.

We studied three variants of the kick velocity distribution. In the first one kick velocities are assumed to have the bimodal velocity distribution (Arzoumanian, Chernoff, Cordes...
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We consider it as the main variant and present the results for it in more details below. For comparison we make calculations for two other distributions. At first we run a variant with significantly lower average velocity. We use single-mode maxwellian with the most probable velocity \(127\ \text{km s}^{-1}\) (it corresponds to the first peak in the Arzoumanian, Chernoff, Cordes (2002) distribution). Then we produce calculations for higher kick velocities. We accept the distribution proposed by Hobbs et al. (2005). It is a single maxwellian distribution with the most probable velocity \(\sim 370\ \text{km s}^{-1}\). In this distribution there are less NSs with small \((\lesssim 200\ \text{km s}^{-1})\) and large \((\gtrsim 700\ \text{km s}^{-1})\) in comparison with the bimodal distribution.

We neglect any dependences of a kick velocity on any parameters, including an evolution in a binary. The latter effect can be significant (Podsiadlowski et al. 2004), however, at the moment no good theory or phenomenology of it exists, so we neglect it. Black hole kicks are assumed to be zero. The critical mass which separates BH progenitors from NS progenitors is assumed to be \(35\ M_\odot\) at the main sequence.

We run the code for two values of the parameter \(\alpha_q\) which characterize the mass ratio distribution of components, \(f(q)\), where \(q\) is the mass ratio. At first, the mass of a primary is taken from a Salpeter distribution, and then the \(q\) distribution is applied.

\[
f(q) \propto q^{\alpha_q}, \quad q = M_2/M_1, \quad q \leq 1
\]

We use \(\alpha_q = 0\) (flat distribution, ie. all variants of mass ratio are equally probable) and \(\alpha_q = 2\) (close masses are more probable, so numbers of NS and BH progenitors are increased in comparison with \(\alpha_q = 0\)).

The distribution of major semiaxes is assumed to be flat in the logarithmic scale in the interval \((10^{-10^7})\ R_\odot\). We used two variants of mass loss rate by normal stars. Moderate mass loss by normal stars was taken according to Vanbeveren et al. (1998), high mass rate was calculated according to papers by the Geneva group (see Maeder, Meynet (2000) and references therein). As the reference variant we consider the one with moderate mass loss, and detailed results (see Table 3) are presented only for this case. Other parameters are typical for the “Scenario Machine”. Detailed description of the “Scenario Machine” and comparison with other codes can be found in Lipunov, Postnov, Prokhorov (1996).

In all runs we calculate 100 000 tracks of massive binaries with minimum mass of a primary \(10\ M_\odot\) (at least one of components produce a NS or a BH). Results are presented in Tables 1 and 2. The first table refers to moderate mass loss scenario, the second – to
enhanced mass loss. Six columns represent numbers for three kick velocity distribution and two choices of $\alpha_q = 2$. To produce percentage of “magnetars” and fraction of binary NSs we add 100 000 NSs which should originate from single stars. Absolute numbers are related just to our runs without any normalization.

Fractions of binary NSs are significantly different for three variants of the kick velocity distribution. For the lowest one we obtain that $\sim 15 - 17\%$ of newborn NSs originated from binary systems remain in bounded binaries (of course, most of the are from the primary components). If in addition to binaries we include the same number of isolated progenitors the fraction goes down to $\sim 8 - 9\%$. For Arzoumanian, Chernoff, Cordes (2002) the fraction of binary newborn NSs is $\sim 6\%$ (without inclusion of single progenitors). Finally, for the distribution proposed by Hobbs et al. (2005) this fraction is $\sim 3\%$.

Not surprisingly, the fraction of “binary magnetars”, ie. NSs originated from progenitors with enhanced rotation which remained bound with their components after a SN explosion, is very low (about a fraction of a percent from the number of “magnetars”). This is due to the fact that most of “magnetars” come from coalescence or from secondary components. In the latter case the more massive star explodes, so more than 1/2 of the system’s mass is

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### Table 1. Results of calculations for moderate mass loss

| Name | Bi–Maxwell | Maxwell, $V_p = 127$ km/s | Maxwell, $V_p = 370$ km/s |
|------|------------|---------------------------|---------------------------|
|      | $\alpha_q = 0$ | $\alpha_q = 2$ | $\alpha_q = 0$ | $\alpha_q = 2$ | $\alpha_q = 0$ | $\alpha_q = 2$ |
| Total number of tracks | 100 000 | 100 000 | 100 000 | 100 000 | 100 000 | 100 000 |
| Total number of NSs | 113 805 | 126 698 | 109 857 | 128 265 | 113 442 | 133 085 |
| Number of binary NSs | 6 604 | 7 065 | 16 466 | 17 814 | 3 116 | 3 242 |
| Fraction of binary NSs | 3.1% | 3.1% | 7.8% | 7.8% | 1.5% | 1.4% |
| Number of ‘magnetars” | 114 | 208 | 397 | 307 | 84 | 145 |
| Fraction of ‘magnetars” | 8.6% | 9.0% | 8.0% | 7.9% | 8.7% | 9.0% |
| From coalescence | 60.1% | 35.7% | 65.4% | 40.4% | 59.3% | 35.0% |
| From primary components | 2.5% | 1.6% | 2.7% | 1.7% | 2.4% | 1.5% |
| From secondary components | 37.4% | 62.7% | 31.9% | 57.9% | 38.3% | 63.5% |

### Table 2. Results of calculations for strong mass loss

| Name | Bi–Maxwell | Maxwell, $V_p = 127$ km/s | Maxwell, $V_p = 370$ km/s |
|------|------------|---------------------------|---------------------------|
|      | $\alpha_q = 0$ | $\alpha_q = 2$ | $\alpha_q = 0$ | $\alpha_q = 2$ | $\alpha_q = 0$ | $\alpha_q = 2$ |
| Total number of tracks | 100 000 | 100 000 | 100 000 | 100 000 | 100 000 | 100 000 |
| Total number of NSs | 126 845 | 145 289 | 121 571 | 137 610 | 126 607 | 145 869 |
| Number of binary NSs | 8 303 | 9 101 | 20 217 | 22 516 | 4 020 | 4 359 |
| Fraction of binary NSs | 3.7% | 3.7% | 9.1% | 9.5% | 1.8% | 1.8% |
| Number of ‘magnetars” | 30 180 | 29 226 | 26 348 | 23 652 | 31 068 | 30 621 |
| Number of ‘binary magnetars” | 157 | 296 | 514 | 795 | 133 | 223 |
| Fraction of ‘magnetars” | 13.3% | 11.9% | 11.9% | 10.0% | 13.7% | 12.5% |
| From coalescence | 56.7% | 65.0% | 65.0% | 36.3% | 55.1% | 28.1% |
| From primary components | 0.7% | 0.8% | 0.8% | 2.2% | 0.7% | 1.7% |
| From secondary components | 42.6% | 68.8% | 34.2% | 61.5% | 44.2% | 70.2% |
lost and there is a very high probability that the binary disrupts. Also it is not a surprise, that for this small fraction of “binary magnetars” the most probable components are BHs; they constitute more than one half of companions. Of course, in all the cases when a BH is one of companions, a “magnetar” is formed from the secondary component of a binary. In general, if a NS is formed from a secondary spined-up component then its companion is a compact object: a BH, a white dwarf, or another NS. If a “magnetar” is formed from a primary component then the secondary is usually at the stage of Roche overflow without common envelope; but the number of such systems in nearly zero. We have to note, that nearly in all cases when a secondary produces a “magnetar” and a primary is a BH there is an episode of a common envelope formation (with synchronization) by the secondary.

Results are sensitive (but not very significantly) to assumptions about mass loss by normal stars (compare Tables 1 and 2). For higher mass loss (Table 2) fraction of magnetars is higher by $\sim 30 - 50\%$.

Fraction of “magnetars” does not depend significantly on kick. The main reason is that more than 1/3 of them (up to 2/3) originate after coalescence of normal stars, and the number of coalescence does not depend on kick at all. The rest of “magnetars” originate from secondary companions. A system usually survives after the first SN explosion even for significant (few hundred km $s^{-1}$) kicks, so again number of “magnetars” is not very sensitive to kicks.

In the Table 3 we present detailed result for the bimodal kick distribution and moderate mass loss. We separate different paths and give percentage of “magnetars” and binary “magnetars” for each channel. Most important paths for NS formation from progenitors with enhanced rotation are coalescence and single Roche lobe overflow by a primary component without a common envelope formation.

### Table 3. Detailed results of calculations for the bimodal kick and moderate mass loss

| Track                                              | $\alpha_q = 0$ | $\alpha_q = 2$ |
|----------------------------------------------------|----------------|----------------|
|                                                    | all            | all            |
| Merge                                              | 60.1%          | 35.7%          |
| Primary RLO with CE+Sync.                          | 1.6%           | 0.2%           |
| Secondary RLO with CE+Sync.                        | 1.4%           | 2.5%           |
| Two RLO w/o CE on Primary                          | 9.4%           | 19.9%          |
| Two RLO w/o CE on Secondary                        | 0.005%         | 0.04%          |
| Single RLO w/o CE on Primary                        | 26.1%          | 39.3%          |
| Single RLO w/o CE on Secondary                      | 0.7%           | 1.4%           |

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3 DISCUSSION

Here we briefly comment on several subjects connected with our study.

3.1 Birth rate of magnetars

Kouveliotou et al. (1998) suggest that magnetars are born with the rate about one per 1000 years, i.e. about few percents of NSs are born with high magnetic fields. Our estimates are in reasonable correspondence with this hypothesis. If highly magnetized NSs are born only from rapidly rotating progenitors then our numbers ($\sim 8 - 9\%$) are good upper limits as without any doubts not all massive stars with angular momenta enhanced during their evolution would produce magnetars.

Note, that an actual value of angular momentum transfer was not calculated by us, also momentum losses after a possible increase were not carefully treated. We do not calculate if the momentum is transfered to the core of the star or not. Tracks just were selected using qualitative criteria. Only for the case of coalescence we can be sure that angular momentum of the core is significantly increased. However, even if only coalescences contribute to formation of magnetars, the number of such NSs is high enough to be consistent with the estimate by Kouveliotou et al. (1998).

3.2 Massive stars and magnetars

Several authors suggested that magnetars should be born from the most massive stars that still could produce NSs (Figer et al. 2005; Gaensler et al. 2005). As it is well known, massive stars ($M \gtrsim 20-25 M_\odot$) extensively loose angular momentum via intensive stellar winds. For such progenitors rotation enhancement in binaries seems inevitable. Unless, as it is noted for example by Tutukov, Cherepashchuk (2004), stars with $M \gtrsim 50 M_\odot$ do not loose angular momentum as they avoid the red supergiant stage. Cameron et al. (2005) suggest few arguments to show that the connection between magnetars and massive progenitors can be not valid (at least in the case of SGR 1806-20). However, this paper was strongly criticized by McClure-Griffiths & Gaensler (2003), and the link between massive progenitors and magnetar candidates seems to be solid. Recently Muno et al. (2005) reported the discovery of an anomalous X-ray pulsar with very massive progenitor (($M \gtrsim 40 M_\odot$). A forty solar masses isolated star would loose its angular momentum due to the stellar wind. This can be
considered as an indirect argument in favor of evolution in a binary if one agrees with the hypothesis about the magnetic field generation used in this paper.

### 3.3 Coalescence of two helium stars

Fryer, Heger (2005) suggested a scenario in which a GRB progenitor is formed after coalescence of two helium stars. They also discuss a possibility of a NS formation via this path. We found such tracks in our calculations: \( \lesssim 1\% \) of all “magnetars” (ie. about 0.1% of all NSs) are formed in this way. So the formation rate of such objects is about 1 in \( \gtrsim 10^5 \) yrs. These values do not show strong dependence on mass loss rate and \( \alpha_q \). We made calculations for both variants of mass loss (moderate and high) and for \( \alpha_q \) equal to 0 and 2: numbers are close to each other. In principle, such sources with high magnetic fields and extreme rotation at birth can produce spectacular manifestations. Similar objects can be formed via coalescence of helium stars with white dwarfs or via coalescence of two white dwarfs. However, we do not study this possibility in details, and the obtained number should be considered as a rough estimate as it depends on many parameters which we do not discuss here (the critical mass which separates NSs from BHs, etc.).

As a by-product we estimate the rate of BH formation after coalescence of two helium stars (no coalescence with white dwarf participation produce BHs). In our calculations with parameters presented in this paper (bimodal kick, two variants of mass loss and \( \alpha_q \)) we do not find any. Changing evolutionary scenario we were able to obtain few. It gives us the opportunity to put an upper limit for formation rate of BHs after coalescence of two helium stars. It is \( \lesssim 5 \times 10^{-6} \) yr\(^{-1}\). Probably we slightly underestimate this number as some of coalescence which is our calculations lead to a NS formation can result in a BH. However, this can not be a significant effect. This value is too low to explain the rate of GRBs.

### 3.4 Velocity distribution

Here we avoid discussing the velocity distribution of magnetars. Basing on associations with SN remnants it was suggested that magnetars can have large spatial velocities (see Gaensler (2004) and references therein). High velocities can appear not only due to large kicks, they can be potentially connected also with a disruption of a binary system after an explosion of a secondary companion (see the discussion of this subject in Iben, Tutukov (1996)). Still, exact velocity determinations for SGRs and AXPs are very welcomed.
We also note that kick velocity was assumed to be uncorrelated with other parameters. However, this is just an assumption. The generation of very large magnetic fields by itself can produce an additional acceleration (due to anisotropic neutrino losses, for example). Fast rotation of a core can lead to fragmentation (Berezinskii et al. 1988) and to high velocity of a compact object. In addition, a kick can potentially influence rotation of a newborn NS (Postnov, Prokhorov 1998; Spruit, Phinney 1998). So, correlations can be extremely important. This subject should be studied separately in more details.

4 CONCLUSIONS

Our conclusions are the following. We made population synthesis of binary systems to derive the relative number of NSs originated from progenitors with enhanced rotation – “magnetars”. With an inclusion of single stars (with the total number equal to the total number of binaries) the fraction of “magnetars” is \(\sim 8-9\%\). Most of these NSs are isolated due to coalescences of components prior to NS formation, or due to a system disruption after the second SN explosion. The fraction of “magnetars” in survived binaries is about 1% or lower. The most numerous companions of “magnetars” are BHs.

ACKNOWLEDGMENTS

We appreciate discussions with Dr. A.V. Tutukov. We want to thank the referee for useful suggestions. The work was supported by the RFBR grants 04-02-16720 and 03-02-16068. S.P. thanks the “Dynasty” Foundation (Russia).

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