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Origin of magnetars in binary systems

Sergei B. Popov*

*Sternberg Astronomical Institute, Lomonosov Moscow State University,
13 Universitetsky pr., Moscow 119992, Russia*

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I review several scenarios of magnetar formation in binary systems via spin-up of a progenitor due to interaction with its companion. Mostly, these evolutionary channels lead to formation of isolated magnetars, and indeed, all well-established sources of this class are single objects. However, some binaries can survive, and several candidates to accreting magnetars have been proposed. I discuss this issue, and conclude that new accretion models can explain properties of the proposed candidates without large magnetic field in correspondence with models of magnetic field evolution.

Keywords: Neutron stars; binary stars; magnetars; evolution

1 Introduction

Magnetars appear as two types of known sources: anomalous X-ray pulsars (AXPs) and soft gamma-ray repeators (SGRs). Now it is well established that magnetars are not very rare and peculiar neutron stars (NSs). A significant fraction of NSs can be born as magnetars. So, these objects are an important part of the general picture of formation and evolution of compact objects. Still, it is not known what determines if a newborn NS is a magnetar or not. Several proposals have been made. For example, it was proposed that magnetars might have very massive progenitors (Muno 2007). Or, that magnetars have progenitors with large magnetic field (Ferrario & Wickramasinghe 2006). However, observational evidence (see below) and theoretical considerations (see Spruit 2008 for a critical discussion of the flux conservation model of magnetar formation) do not support the universality of such scenarios (which does not exclude that they can be applicable in some cases).

In this note, based on a talk presented in September 2014 at the conference "Ioffe Workshop on GRBs and other transient sources: twenty years of Konus–Wind Experiment" in St. Petersburg (Russia), I briefly review different proposals related to evolution of magnetar progenitors in binary systems. In addition, I discuss magnetar evolution in accreting X-ray binary systems, and comment on related issues.

*Email: polar@sai.msu.ru

2 Observational evidence for magnetar origin in binaries

There is evidence that magnetars can originate from close binary systems. The first indirect indication was presented by Davies et al. (2009). These authors analysed data on SGR 1900+14 and discussed several realistic scenarios of formation of this source in a binary system. However, the main argument appeared very recently (Clark et al. 2014).

Clark et al. (2014) studied the magnetar CXOU J1647-45. It was proposed before that this NS might have a very massive progenitor (Muno et al. 2006). Clark et al. (2014) observed a massive runaway star in the young cluster Westerlund 1. Analysis of its history demonstrated that it might be born in a binary system, disrupted after a SN explosion. The runaway star is the former primary (initially more massive) component of the binary, the secondary component became a progenitor of the magnetar CXOU J1647-45.

In this scenario the important point is that the progenitor of the magnetar enhanced its angular momentum during evolution in the binary. This can be an important feature which allows us to understand what is special about magnetar formation. And it confirms the main prediction of theoretical scenarios of magnetar formation in binaries, proposed several years ago.

3 Theoretical scenarios of magnetar formation in binaries

Before the first observational evidence of the origin of magnetars in binary systems appeared, we have studied possible evolutionary channels for magnetar formation in binaries (Popov & Prokhorov 2006; Bogomazov & Popov 2009).

The main motivation for our first study was a little bit peculiar. Even up to now all well-established magnetars (SGRs and AXPs) are isolated objects (see the catalogue in Olausen & Kaspi 2014). Most of massive stars are born in binaries, and about 10% of NSs remain in binary systems after supernova (SN) explosions. So, it seemed reasonable to look at evolutionary channels which, on the one hand result mostly in single NSs, and on the other hand – maximize the probability of magnetar formation.

In the original magnetar model by Thompson & Duncan (1993) it is proposed that huge magnetic fields are generated by a dynamo mechanism. So, rapid initial rotation is necessary. However, stellar cores can efficiently lose angular momentum when a star enters the red (super)giant stage if magnetic fields contribute to the angular momentum redistribution (e.g. Langer 2012, and a recent review Yoon 2015). Thus, it is necessary to enhance rotation. The only effective way to do it is to transfer angular momentum in a binary system (substellar components also can be in the game). In our studies we used population synthesis (Popov & Prokhorov 2007) to identify evolutionary tracks of binary systems which allows us to enhance rotation of NS progenitors. Then we calculated the fraction of such systems, and the fraction of isolated NSs formed through such channels.

Note that a similar problem was discussed in the context of gamma-ray burst (GRB) progenitors (see a review and references in Yoon 2015). In this phenomenon

rotation also can play a crucial role. Then potentially, evolutionary channels for magnetar formation and for GRB progenitors can be similar, just in the case of GRBs a black hole (BH) formation might be required (magnetars can also power GRBs, see a review of mechanisms in Woosley 2011).

In addition, several studies indicated that some magnetars can have very massive progenitors (Figer et al. 2005; Muno et al. 2006). Potentially, it can also fit the binary evolution scenario, as mass loss in a binary can result in smaller core mass, and so it opens the possibility to form a NS from initially very massive progenitor, which otherwise might produce a BH. However, we did not study such evolutionary channels.

3.1 Optimistic scenario of magnetar formation is binaries

In the first study (Popov & Prokhorov 2006) we made an optimistic assumption that after rotation of a progenitor is enhanced it is not significantly reduced. That is, an NS can increase its magnetic field due to a dynamo mechanism if the progenitor gained angular momentum at any stage of its evolution.

There are the following main possibilities to spin-up a star in a binary:

- merger;
- accretion mass transfer;
- tidal synchronization.

We analysed all of them.

We obtained that the fraction of NS progenitors with enhanced rotation is larger than the expected fraction of magnetars among all NSs. This is good news, as clearly not all NSs born from such progenitors are necessarily magnetars.

We also obtained that it is easy to reproduce the large fraction of isolated magnetars. The main channels for magnetar formation in our study are coalescences and spin-up of the secondary companion (mostly, binaries are destroyed after the second explosion: the fraction of survivors is low enough to be consistent with the present-day magnetar statistics). It is interesting to note that if a magnetar remains in a binary after the SN, then the most probable companion in this scenario is a BH.

Many magnetars in this scenario (as well as in the pessimistic scenario, see below) are expected to be born after SN Ib/c (see Yoon 2015 for discussion of SN Ib/c progenitors, especially in binaries). Also it is important to note that in this evolutionary channel NSs can be formed from low-mass stars, which can leave a white dwarf if they evolve in isolation.

3.2 Pessimistic scenario

To be on the safe side we also studied another scenario (Bogomazov & Popov 2009). Here we assumed that a star might be spun-up after the helium core formation in a very close binary due to tidal synchronization. This guarantees that the angular momentum is not lost before the SN. Our analysis demonstrated that we are interested only in systems with orbital period less than $\sim$10 days at the moment of synchronization, because only they can produce NSs rotating rapidly enough. Of course, the fraction of NSs which passes through such a channel is smaller than in the optimistic

scenario. However, it is still consistent with magnetar statistics, i.e. the total number of NSs born from such progenitors can (barely) fit the number of magnetars.

The problem is with solitarity of magnetars. Most of NSs spun-up in such close systems remains in binaries after a SN explosion. To reproduce the fraction of isolated magnetars we have to assume that kick is larger for such objects than for the whole NS population. Typical values might be above $\sim$(500–700) km s^{-1} depending on additional assumptions (velocity distribution, correlation with spin axis, etc.)

Observations of magnetar spatial velocities do not support the hypothesis that these sources have significantly larger velocities than other NSs (see Tendulkar et al. 2013 and references therein). So, we do not think that this pessimistic scenario is very promising. However, this channel can contribute to the magnetar population. Mostly, magnetars formed through such a channel remain in compact binaries. The most probable candidates are main sequence stars and, again, BHs.

4 Magnetars in binaries

At the moment no classical magnetars (i.e., SGRs or AXPs) are known to be members of a binary. Obviously, nothing can prevent detection of an SGR flare in a binary, but no such cases are known. Also it is important to note that known SGRs are mostly very young objects, and it is very unlikely that the secondary companion in the binary could previously significantly influence properties of the magnetosphere or/and crust of the magnetar, so that its activity terminated due to mass transfer. On the other hand, there are several claims that few NSs in accreting X-ray binaries can have large magnetic fields.

Determination of magnetic fields of accreting NSs are mostly based on indirect model dependent methods related to spin-up or/and spin-down (unless cyclotron lines are detected), see Revnivtsev & Mereghetti (2014). Below we discuss several subjects related to the problem of magnetars in binaries.

4.1 Field decay and HMXBs

X-ray binaries are mainly divided into two wide classes: low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs). On average LMXBs are old systems. So, NSs in them are significantly evolved, and their magnetic fields might be decayed. In addition, strong accretion (typical for LMXBs) can result in strong decrease of magnetic fields, and we observe it in millisecond pulsars. Then we can focus on HMXBs.

Many times during the last 35-40 years, different authors have tried to estimate magnetic fields of accreting NSs using approaches similar (or identical) to those described by Davies et al. (1979) (see, for example, Lipunov & Popov 2001 and references therein). In many cases estimates of magnetic fields produce very large (magnetar scale) values. However, such estimates depend on the model of accretion (see for example Klus et al. 2014, where the authors under certain assumptions obtained large field values for many NSs in Be/X-ray binaries). Recently, a new one was proposed for quasispherical accretion with significantly sub-Eddington rates (Shakura et al. 2012).

Comparison of the new Shakura, Postnov et al. model with old ones was made by Chashkina & Popov (2012). Several tens of Be/X-ray binaries in the SMC were used to obtain distributions of NS magnetic fields calculated with different approaches. Results have been compared with predictions of the field decay model developed by Pons et al. (2009). In this model magnetar fields decay down to $\sim$few$\times10^{13}$ G on the time scale $\sim$few$\times10^5$ yrs.

Analysis showed that only in the case of the Shakura, Postnov et al. model there are no high magnetic fields, as expected from the model by Pons et al. As significant field decay in magnetars on the time scale of several million years look inevitable, we conclude that at the moment the model by Shakura, Postnov et al. is the best description of low-rate accretion in wind-fed X-ray binaries.

4.2 SXP 1062

Interestingly, it is possible to identify a former magnetar in a binary system. The source SXP 1062 in the SMC was proposed as an example (Popov & Turolla 2012).

SXP 1062 is a unique system because the age of the NS is known thanks to discovery of a SNR related to the source (Hénault-Brunet et al. 2012; Haberl et al. 2012). As it is young (age $\sim$(2–4)$\times10^4$ yrs), there is a possibility to reconstruct its history. Our study demostrated that either initial spin period was uncomfortably long ($\sim$1 sec)*, or the NS initially had a much larger magnetic field, $B \sim 10^{14}$ G, which then decayed. This allows the NS to start to accrete matter from the companion's stellar wind after reasonably short interval of time. The present day field was estimated according to the Shakura, Postnov et al. model (see Shakura et al. 2012 and Shakura et al. 2013), and it is well below the magnetar value.†

4.3 Other magnetar candidates in binaries

Several other sources were also proposed to contain accreting magnetars. The list includes GX1+4, 4U 2206+54 (Reig et al. 2012), Swift J045106.8-694803 (Klus et al. 2013), and some others. Several of them have been discussed by Postnov et al. (2014). In the new model of settling accretion angular momentum is more effectively transported outwards from a NS due to convection in the envelope. So, for example, the equilibrium period (for the same value of the magnetic field) in the model by Shakura, Postnov et al. is longer than in earlier models.

Postnov et al. (2014) conclude that in the framework of the new settling accretion model properties of the observed sources can be explained with standard magnetic fields; i.e., a strong assumption of huge magnetic fields survival is not necessary. This is in correspondence with our studies (Chashkina & Popov 2012; Popov & Turolla 2012).

*This possibility was initially proposed by Haberl et al. (2012).

†Note that estimates based on older theories provide magnetar-scale field.

5 Hidden magnetars

The term was coined long ago by Geppert et al. (1999) to label the case when the magnetar field is overwhelmed by plasma after a SN explosion. We write "long" because just very recently the idea of submerged field became very popular in NS studies (Ho 2011; Viganò & Pons 2012). A NS for several thousand or tens of thousand years can appear as a weakly magnetized source because its field has been covered (screened) by a significant amount of matter (comparable with the crustal mass – $\sim 10^{-3}\,M_{\odot}$) accreted during a fall-back episode.

Shabaltas & Lai (2012) demonstrated that the NS in SNR Kes 79 can be a "hidden" magnetar, as it has a very large (64%) pulse fraction. Recently, we analysed properties of the NS in SNR RCW103 (Popov et al. 2015), and concluded that it also can be a "hidden" magnetar as the flux of this source changes in the way compatible with a magnetar activity due to additional heat release in the crust.

Potentially, a compact object in the SN1987A can be a "hidden" magnetar. Now it is confirmed that the progenitor was a member of a binary, which merged not long before the SN explosion (Morris & Podsiadlowski 2007). This perfectly fits our scenario for magnetar formation in binaries. Thus, as no traces of the presence of a magnetar is noticed, we can conclude that the source is a "hidden" one.

6 Discussion

6.1 Alternatives to spinning up the core

In Sec. 2 we presented two scenarios of magnetar formation in binary systems where rotation of a progenitor has been enhanced due to interaction with a companion. However, binary evolution is not just the way to spin-up a star, it can also reduce spinning down of a NS progenitor. Evolution in a binary system can reduce the duration of the red (super)giant stage (see Maeder & Meynet 2014 about spin-down of a stellar core on this stage), so that angular momentum losses by a stellar core are smaller (see, for example, discussion in Clark et al. 2014). This adds new possibilities to form a magnetar in a binary system.

6.2 Variety of evolutionary channels

It looks quite natural that evolution in a binary can lead to relatively rapid rotation of the core of a progenitor. It is known that some evolved stars, including Ib supergiants, have rapid rotation (see Rodrigues da Silva et al. 2015 and references therein), which can be due to merging, or due to "consumption" of a substellar companion. Still, it is possible that a core can be spun-up just before a SN explosion. Such models have been recently studied by Fuller et al. (2015).

These authors demonstrated that in some cases internal gravity waves can spin-up a stellar core already at the red supergiant stage. Thus, this can result in formation of NSs with millisecond spin periods, and potentially – in a magnetar formation via a dynamo mechanism. Also this mechanism can explain magnetars in wide binaries, like SXP 1062.

6.3 GUNS and magnetars in binaries

Most of massive stars are born in binaries. So, most of NSs are born from members (may be former) of binary systems. In many cases evolution in a binary could influence properties of the progenitor, and so – play a role in determining initial parameters of an NS. Then, in its final form the Grand Unification of NSs,[‡] – GUNS (see, for example, Igoshev et al. 2014) – might include ingredients related to binary evolution.

Up until now, known NSs in binary systems do not show systematic deviations in their initial properties (increased masses and decreased magnetic fields in millisecond pulsars are due to long term evolution of NS in accreting binary systems). But this can be a selection effect. For example, by definition, NSs in close binaries are not products of mergers. Or initial parameters are "forgotten" as we observe evolved and relatively old systems.

Studies of NS properties in HMXBs can help to probe evolution of compact objects on the time scale from few to tens million years, and first steps are already done. More young binary systems (especially with known ages) also can help a lot in determining initial parameters and evolutionary laws of NSs.

In particular, studies of possible (may be former) magnetars in binary systems can shed light on the origin of these objects. Diversity of observational data favours different channels of magnetar birth. For example, SXP 1062, if indeed it is an evolved magnetar originated from the primary component of the binary, tells us that spin-up of a progenitor is not a necessary condition to form a magnetar. Conversely, CXOU J1647-45 favours the scenario studied by Popov & Prokhorov (2006). Clearly, we need more data to understand the role of binary systems in producing different types of NSs.

7 Conclusions

There are ∼30 magnetars, including candidates (Olausen & Kaspi 2014). All of them are isolated sources. On other hand, in the standard paradigm of the dynamo mechanism field enhancement, it is favourable for a magnetar to be born in a binary system from a companion which has been spun-up. Then, the main channels of magnetar formation are either related to mergers, or to the system disruption. It is not easy to prove this scenario, but observations start to support this model.

In some cases the system can survive, and the magnetar can be observed in an X-ray binary. However, as large magnetic fields rapidly decay down to standard values, it is very improbable to find an active magnetar in an X-ray binary. Most probably, we find an evolved magnetar, and it is non-trivial to reconstruct its evolution to prove that before it has been a strongly magnetized compact object.

Understanding of the role of binary systems in formation of magnetars (and may be in influencing parameters of some other types of compact objects) can be crucially important in understanding initial properties of NSs.

[‡]The term was proposed by Kaspi (2010).

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