Neutron star high mass binaries as the origin of SGR/AXP

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Abstract. A close high-mass binary system consisting of a neutron star (NS) and a massive OB supergiant companion is expected to lead to a TZO structure, which consists of a NS core and a stellar envelope. We use the scenario machine program to calculate the formation tracks of TZOs in close high mass NS binaries and their subsequent evolution. We propose and demonstrate that the explosion and instant contraction of a TZO structure leave its stellar remnant as a soft gamma ray repeater and an anomalous X-ray pulsar respectively.

Key words. star, massive – stars: accretion – binaries: common envelope – stars: collapse

1. Introduction

A neutron-star high-mass binary (NS/HMB) system consists of a neutron star (NS) and an OB spectral type massive companion (typically \( > 10 \, M_\odot \)), which falls into two classes, i.e. Be and supergiant companions. NSs accrete material by different means from different types of massive companions, manifesting themselves as high-mass X-ray binaries (HMXBs) – Be X-ray binaries (BeHMXBs) or supergiant X-ray binaries (sgHMXBs, for details, see Chaty 2011). BeHMXBs usually have a wide and eccentric orbit, and the NSs accrete matter via circumstellar "decretion" disk created by low-velocity (\( \sim 10^7 \, M_\odot \)) and high-density stellar wind from Be donor stars. The NSs in sgHMXB systems, orbiting on a circular orbit, accrete material from the OB supergiant donor star, by means of both Roche lobe overflow (RLOF) and wind-fed accretion. The sgHMXB phase lasts \( \sim 10^{5-5} \) years and subsequent mass transfer is very large and rapid, in which a super-Eddington accretion rate may be involved.

In close massive sgHMXB systems which experience a super-Eddington accretion, a milestone during their evolution is called the "common envelope (CE) phase", which is initiated when the supergiant companion overflows its Roche lobe and engulfs the NS (e.g. Paczynski 1976). In a CE, the angular momentum transportation from two orbiting components to the NS core is caused by the velocity difference between two cores and CE. Consequently, the NS and stellar core are forced to get closer and closer. According to different properties of the system, the remnants of the CE phase will possess distinct nature (see Iben & Livio 1993 for a review). One appealing and rare consequence of CE evolution is the production of a TZO structure (Thorne & Zytikow 1975, 1977), which consists of a NS core and a massive stellar envelope and is formed by the complete coalescence of NS with the stellar core of the OB supergiant companion.

In this paper, we investigate the fate of the TZO structure and its connection to the origin of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). TZOs fall into two classes (Eich et al. 1989): "giant" TZOs (with low-mass envelope of \( < 8 \, M_\odot \) and dominated by gravitational energy) and "supergiant" models (with massive envelope of \( > 10.5 \, M_\odot \) and 95% energy provided by nuclear burning). We use the scenario machine program (Lipunov et al. 2009) to calculate the evolutionary tracks for both giant and supergiant models. In section 2, we describe the selection for input parameters and the evolutionary paths. We present our calculated results in section 3. Section 4 contains discussions and section 5 is a brief summary.

2. Calculations

We use the scenario machine code (Lipunov et al. 2009) to calculate the formation of TZO in close NS/HMBs and the subsequent evolution, in order to study its connection to the origin of SGR/AXP. The code was initially designed in early 1980s to calculate the evolution of NS in massive binaries (Kornilov & Lipunov 1983a, 1983b), and was already developed into a program package (see Lipunov, Postnov & Prokhorov 1996a, 1996b for detailed description), which incorporates all current scenarios of binary evolution and is used to carry out numerous calculations (for a review see Lipunov et al. 2009).

We mainly aim to trace the evolution of NS/HMB systems during the last \( 10^{5-5} \) yrs of the TZO phase as well as their remnants after the CE ejection. In our calculations, we consider those close systems in which RLOF transfers matter from the massive supergiant star to NS at a super-Eddington rate. The sgHMXB systems always have low eccentric or circular orbits...
The evolution and fate of a binary system mainly depend on three essential properties, i.e. the mass of the initially more massive star ($M_1$), the mass of the initially less massive star $M_2$ (or the mass ratio $q = M_2/M_1$), and initial orbital separation ($a_0$, or orbital period $P_{\text{orb}}$). Since we only deal with massive binary NS systems, the initially more massive star should be restricted to be between roughly 9 $M_\odot$ and 30 $M_\odot$ (Heger et al. 2003), in order to ensure that the compact object left behind supernova explosion is a NS. In the formation channel of NS/HMXB systems, the initially more massive star should be capable of evolving off the main sequence during less than $10^5$ yrs and finishing the rest of its evolution rapidly (in $\sim 10^3$ – $10^6$ yrs). According to the scenario for formation and evolution of HMXBs (van den Heuvel 1983; van den Heuvel 1992; van den Heuvel 2001), the thermal timescale ($t_\text{th} \equiv \text{thermal energy} / \text{angular momentum} \propto M^{-2}$) of the initially less massive star should not be longer than that of the initially more massive star by more than one order of magnitude, which implies that the rough lower bound of companion mass is $M_2 \geq \frac{1}{3} M_1$, i.e. $q \geq 1/3$ (Bhaskaran & Goss 2012). Therefore, the range of primordial binary mass ratio is $0.3 \leq q \leq 1$ for the formation of NS/HMXB.

During collapse of massive stars, not all matter collapses to form the NS. In order to produce a NS with mass of $\sim 1.4 M_\odot$, we take the collapse mass fraction as 30% (Lipunov, Postnov & Prokhorov 1996a, 1996b; Lipunov et al. 2009), i.e. 30% mass of helium (or Wolf-Rayet) stars will collapse and form NS.

In order to have core coalescence during the CE phase, the initial orbital separation $a_0$, on one hand, should be large enough so that the condition of RLOF can be met when the initially more massive star evolves off the main sequence, without which there would be no mass transfer and the HMXB formation scenario will not operate. On the other hand, the system should close enough after the NS formation, in order to ensure a complete coalescence of NS with the stellar core of the supergiant companion in CE.

In this work, we are interested in the evolution and fate after the core coalescence of NS and the stellar core of the companion. The additional kick velocity achieved during supernova explosion will only affect the survival probability of HMXBs, not their subsequent evolution. We therefore assume that the supernova explosion is symmetric and do not take into account the kick velocity in each track.

Because of the short duration of HMXBs, the magnetic field of NS in HMXB is approximately $10^{12}$ G. We do not take the magnetic-field decay into consideration in our calculations.

We assume that the matter from the companion during RLOF is totally accreted onto the primary and set the efficiency of the angular momentum loss during the CE phase to be 100%. To ensure the complete evolution of TZO and investigate its final remnants, we calculate the evolutionary track for a duration of $10^{10}$ yrs.

### 2.2. Evolutionary scenarios and physics

In the evolutionary path descriptor in the scenario machine code, we consider the following:

1. Evolution of two components, supernova explosion of the initially more massive star and formation of NS – The physics in these stages is not of direct relevance to our discussion in this paper. Interested readers can check Lipunov et al. (2009) for details.

2. RLOF of the supergiant companion before the CE phase – In this scenario, NS is in the regime of super-accretor and accretes material from the supergiant companion at a super-Eddington accretion rate ($\sim 10^{-3} – 10^{-5} M_\odot/yr$). This stage lasts very short time, e.g. $10^3$ yrs if the mass of the resultant TZO is less than $5 M_\odot$, a few hundred years if that mass is more than $5 M_\odot$, a few tens years for a supergiant TZO, whose mass is more than $11.5 M_\odot$ (see Fig. 1 and Fig. 2 for details).

3. RLOF of the supergiant companion star during the CE stage – NS is still a super-accretor and accretes material from the stellar envelope. In addition, the velocity difference between two cores and CE causes a drag force, which transfers the orbital angular momentum of two cores to the CE. Consequently, the NS and stellar core of the companion are forced to get closer and closer. In this scenario, the RLOF occurs in dynamical timescale and lasts $\sim 10^4$ yrs.

4. Coalescence of NS with the stellar core inside CE – For systems in which the orbital period ($P_{\text{orb}}$) of two cores at the onset of CE is less than a minimum period ($P_{\text{min}}$, e.g. Taam, Bodenheimer & Ostriker 1978; van den Heuvel 1989, 1996), the NS spirals deeply into the center and coalesces with the stellar core, forming a TZO structure (Thorne & Zykow 1975, 1977).

5. Subsequent evolution of the TZO structure – For the evolution of stellar envelope, see Lipunov et al. (2009) for details. The fate of TZO depends on its mass and the energy source (Thorne & Zykow 1977; Podsiadlowski 1996). To determine the properties of remnants, we set the Oppenheimer-Volkov limit as $2 M_\odot$ (Demorest et al. 2010).

### 3. Results

Using the scenario machine code and based on the physics discussed in section 2, we calculate the evolution of several NS/HMXB systems, which leads to the formation of a giant TZO and supergiant TZO, respectively.

#### 3.1. Giant TZO

We study four cases of systems with different initial properties to have resultant TZO structures of different masses. The initial properties for each system are listed in Table 1. These four cases are the following:

- **Case-A** – Initial maximum mass ratio ($q=4/5$) of systems which will produce the most massive giant TZO ($M_{\text{TZO}} = 9 M_\odot$).
- **Case-B** – Systems with initially intermediate mass ratio ($q=3/4$).
- **Case-C** – Systems with initial minimum mass ratio ($q=1/3$) which will lead to an intermediate giant TZO.
Table 1. Initial input parameters which produce different giant TZO systems.

| Case | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $P_{\text{orb}}$ (d) |
|------|-------------------|-------------------|-------------------|
| A    | 15                | 12                | 1                 |
| B    | 12                | 9                 | 2                 |
| C    | 15                | 5                 | 2                 |
| D    | 10.5              | 3.7               | 1                 |

Notes: $M_1$ is the mass of initially more massive star. $M_2$ denotes the mass of initially less massive star. $P_{\text{orb}}$ represents the initial orbital period.

Case-D – Systems with initial minimum mass which can produce a giant TZO with mass $M_{\text{TZO}} < 5M_\odot$.

We plot the evolution of mass and spin period in Figure 1. To produce a massive giant TZO structure, the initial components should have a mass ratio of $q \leq 4/5$, above which the systems will coalesce before the supernova explosion of initially more massive star. It takes about $10^5$ yrs for a NS/HMXB with an OB supergiant companion to evolve into the CE phase, which lasts for about another $10^5$ yrs. Then the coalescence of the NS and the stellar core occurs and a giant TZO structure is ultimately produced. The duration of this TZO phase is $10^5$ yrs until the stellar envelope is completely ejected. In Case-A, the mass of the TZO remnant is $1.5 M_\odot$. However, in the other three cases, the mass of remnants is $1.6 M_\odot$. Generally speaking, the radius of TZO remnants is of the order of that of canonical NS, and their spin period is about a few seconds. It seems that the radius of TZO remnants is mildly related to the total mass of TZO. However, the spin period of TZO remnants seems not to be sensitive to that of the stellar envelope of TZO (see Fig. 1 for details).

Table 2. Initial input parameters which lead to different supergiant TZO. The meaning of parameters is same as that of Table 1

| Case | $M_1$ ($M_\odot$) | $M_2$ ($M_\odot$) | $P_{\text{orb}}$ (d) |
|------|-------------------|-------------------|-------------------|
| A    | 20                | 18                | 8                 |
| B    | 25                | 20                | 8                 |

3.2. Supergiant TZO

To investigate the evolution and fate of supergiant TZO models, we calculate the following two cases:

Case-A – Systems with the initially minimum mass which can lead to a supergiant TZO structure.

Case-B – Systems with initially maximum mass ratio ($q=4/5$).

Assuming that the maximum mass of NS is $2.0 M_\odot$, we choose the initial properties as shown in Table 2.

Figure 2 presents the results. The duration of the TZO phase ($10^5$ years) is the same as that of giant models, that is, the evolution time of a TZO is independent of its mass. The remnants in both cases have mass of $1.5 M_\odot$. The radius in case-A is the same as that of a normal NS, while in case-B it is smaller, only about $5-6$ km. The spin periods are also a few seconds, which are not sensitive to that of the stellar envelope of the TZO (see Fig. 2 for details).

4. Discussions

4.1. Nature of TZO remnants

A typical TZO structure consists of a convective stellar envelope, a radiative and approximately isothermal halo, and a NS core (see Fig. 1 in Thorne & Zytkow 1977 for details). In giant TZO structure, the convection in the envelope is ineffective. The gravitational energy released by mass flows contributes to two effects, i.e. X-ray emission and heating the inflows. The latter leads to huge gravitational energy deposited (Thorne & Zytkow 1977), which is released via nuclear burning and carried away by electron conductivity and neutrino runaway. The strong neutrino runaway may couple with the runaway temperature and accretion rate, responsible for a catastrophic contraction of the TZO and the ejection for part of the envelope. The rest of the envelope forms a debris disk gradually accreted by the TZO remnant.

However, the energy source of a supergiant TZO is the nuclear burning energy via rp-process (Biehle 1991; Cannon et al. 1992; Cannon 1993). There are two different scenarios according to the means by which nuclear burning terminates. If the rp-process seed elements in the envelope are exhausted (Biehle 1991) and no other energy source can be tapped, the envelope will collapse and squeeze the hydrostatic structure of the inner region. Accordingly, the surroundings near the NS core reaches a denser region with higher pressure and temperature. When the gravitational potential of the NS core can not support the higher pressure and density, the collapsed TZO structure explodes and ejects part of the material in the envelope. On the other hand, if the mass of the envelope decreases to be below the minimum mass for nuclear burning via intense stellar wind (Podsiadlowski 1996), the supply of fresh fuel is choked off and a radiative region develops. Then, the neutrino runaway becomes the dominant energy-loss mechanism, which ultimately leads to the contraction of the structure. Moreover, the dense environment is responsible for leaving a fallback disk or a debris disk after the explosion or instant contraction respectively, which results in an isolated accreting compact object.

The nature of the isolated accreting compact object depends on the mechanism by which a TZO structure is disrupted, that is, explosion or contraction. Generally speaking, neutrino runaway leads to an instant contraction, and the exhaustion of rp-process seed elements results in the explosion of TZO. From our results, the remnants of different TZO structures are always objects with mass of about $1.5-1.6 M_\odot$. However, the radius of remnants is different. The remnants left behind a giant model and Case-A of the supergiant model have a radius similar to that of normal NS radius, while that resulted from supergiant model Case-B has a radius of about $5-6$ km. Accordingly, the equation of state for remnants with normal NS radius should be the same as a canonical NS. Furthermore, due to the deposit of thermal energy above NS surface (Wang & Chang 2013, and reference therein), which is converted from gravitational en-
energy (in giant models) or nuclear burning energy (in the case of supergiant TZO), the remnant formed by means of instant contraction of TZO is, in nature, a normal NS with higher surface temperature. The material in the original stellar envelope is surrounding the NS, forming a debris disk. However, the formation of objects with 5-6 km radius is related to the explosion of a supergiant TZO with convective envelope. We expect the collapse and explosion are catastrophic and can change the state of the crust of the original NS core, producing a denser crust. Part of ejected envelope falls back and forms a fallback disk around the newborn object.

4.2. Possible observations

In a solitary accreting system, accretion from a fallback disk may contribute to two effects, that is, X-ray emission and ac-
crention torque. Consequently, we can divide the accretion rate into two parts, $M = M_1 + M_2$, in which $M_1$ dominates X-ray emission and $M_2$ results in an accretion torque. The net effect of these two parts is responsible for the angular momentum of accreted material and have influence on the spin of compact object. According to Menou et al. (1999), the angular momentum carried by the accreted matter is dominated by the torque,

$$J = I \dot{\Omega} = M_1 R_A^2 \Omega_k(R_A) - 2 M_1 R_A^2 \Omega_k(R_A) \frac{\Omega_s}{\Omega_k(R_A)},$$

(1)

where $R_A \approx \left(\frac{B^2 c^6}{G M^3 \sqrt{2}}\right)^{2/7}$ is the Alfvén radius, $\Omega_s = 2\pi/P_s$ ($P_s$ is the spin period of star), $\Omega_k(R_A)$ is the Keplerian angular velocity at $R_A$, $I$ is the moment of inertia, $M$ is the mass of the remnant, $G$ is the gravitational constant, $R$ is the radius of the remnant. We assume that the magnetic field is the same as that of a normal NS, and take the observed typical luminosity ($10^{34} - 10^{36}$ ergs/s) and spin-down rate ($10^{-11} - 10^{-13}$ s/s) of SGR/AXP into consideration. The change of angular momentum ($J = I \dot{\Omega}$) is at a rate of $\sim 10^{39-31} g \text{cm}^2 / \text{s}^2$ for remnants with radius of 5-6 km and of $\sim 10^{30-2} g \text{cm}^2 / \text{s}^2$ for remnants with radius of canonical NS. According to the Alfvén radius ($R_A \approx \left(\frac{B^2 c^6}{G M^3 \sqrt{2}}\right)^{2/7}$) and $\Omega_k(R_A) \propto R_A^{2/3}$ and due to the same order of $M_1$ and $M_2$ (Menou et al. 1999), the spin period of remnants with smaller radius is mildly shorter than that with radius of canonical NS.

A normal NS with higher surface temperature, formed after instant contraction of TZO, manifests itself with persistent X-ray emission via steady accretion from the debris disk, such as 1E 1048.1-5953 and 1E 2259+586 (Woods & Thompson 2006; Mereghetti 2008). However, to keep the thermal dynamical equilibrium, the deposited thermal energy will occasionally release as X-ray enhancements or short energetic bursts. The remnants formed after an explosion of a TZO structure can emit mildly harder X-ray luminosity, due to the accretion onto a denser surface. We expect that the repeated soft γ-ray burst emission and bright outbursts are related to the reconstruction of dynamic equilibrium after the clumpy accumulation of accreted material onto the denser surface, and it needs to be further investigated. If this object is in a stellar cluster, the perturbation by passing field stars may result in the sudden change of accretion rate, which also can be responsible for the outbursts. According to Eq. (1) if we assume a steady change rate of angular momentum, a higher spin-down rate corresponds to a smaller radius and thus likely a denser crust. A smaller radius and a denser crust will produce photons of higher energy when clumps of matter from the accretion disk hit the stellar surface. Therefore the emission from SGRs is generally at higher energy than that from AXPs, which is consistent with the observations (Mereghetti 2008).

Based on the above discussion, we propose that the remnants with radius of canonical NS, left behind an instant contraction of TZO, should be an AXP, which is a normal NS with higher surface temperature, accreting from a debris disk. On the other hand, the explosion of TZO can lead to an object with a smaller radius (5-6 km) and a denser crust, which manifests itself as a SGR.

### 4.3. Birth rate

So far, there are 13 SGRs (9 confirmed and 4 candidates) and 13 AXPs (11 confirmed and 2 candidates) detected (see McGill SGR/AXP online "http://www.physics.mcgill.ca/~pulsar/magnetar/main.html" for an updated catalogue). Considering the typical age of this class of objects, Kouveliotou et al. (1998) suggests that they are born at a rate of about one per millennium.

There are 114 HMXBs (+ 128 in the Magellanic Clouds) in the catalogue of Liu, van Paradijs & van den Heuvel (2006), in which sgHMXBs account for 32% (Chaty 2011). We expect one SGR/AXP will be produced in every four sgHMXB systems. Considering that the formation of SGR/AXP from HMXBs just involves sgHMXBs, the birth probability of SGR/AXP in HMXBs is about 7%.

In addition, the formation of SGR/AXP involves close and RLOF systems, which can lead to complete coalescence of two components. Taking the evolutionary timescale from the formation of sgHMXBs to the formation of TZO remnants (~ $10^6$ yrs, see Fig. 1 and Fig. 2) into consideration, the birth rate, in galactic field, via this mechanism is lower than 6 per ten millennium. However, if the system is located in massive stellar clusters, in which the physical star-star encounter frequently occurs, the probability will be enhanced. Because massive stellar clusters always involve young clusters, we expect the TZO remnant produced by this way should be associated with the supernova remnant of the earlier supernova explosion.

### 4.4. Application to sources

Among the observed SGRs and AXPs, there are three SGRs associated with massive star clusters (see McGill SGR/AXP online "http://www.physics.mcgill.ca/~pulsar/magnetar/main.html" for details), which display both bursts and giant flares, while the others only shows burst emission. A massive star cluster contains young and short-lived massive stars. Taking SGR 1806-20 as an example, it is surrounded by at least four Wolf-Rayet stars, three OB stars, and a luminous blue variable. The motion of these massive stars will perturb the accretion of SGR from its fallback disk, which may lead to some non-steady accretion and manifest as outbursts. If a star passes through the SGR system, the influence will be significant, and a catastrophic accretion may occur. Consequently, massive clumps are accreted and strike the dense surface, contributing to a sudden enhancement of luminosity. The striking energy converts into thermal energy which is gradually radiated and demonstrates a long pulsating tail.

For the case of AXPs, the debris disk is more massive than the fallback disk of SGR, so the influence of passing stars should be stronger. When a massive star passes by or through the AXP system, the collision or gravitational interaction may produce fragments which are ejected outside the debris disk. The residual angular momentum will be either prograde or retrograde, which imposes an impact on the central NS and leads to glitch or anti-glitch. On the other hand, the change of angu-
lar momentum is responsible for a sudden change of accretion rate, according to Eq. [1], which is manifested as outbursts.

5. Summary

In this paper, we study evolution and fate of the TZO structure whose formation involves close HMXBs containing a NS and an OB supergiant companion. We discuss the connection between the remnant of a TZO structure and SGR/AXP. In our calculations, we use the scenario machine code to calculate both giant and supergiant TZO models, according to different initial input physics. We find that the giant TZO and supergiant TZO with ineffectively convective envelope will instantly contract and produce an object with a radius of normal NS (∼10 km), and that a supergiant model with convective envelope may explode and result in an object with a radius of 5-6 km.

Based on the evolutionary physics, we conclude that the remnant, left behind an instant contraction of TZO, should be a normal NS with higher surface temperature, because of the deposited thermal energy during TZO phase. The contracted material in the stellar envelope forms an debris disk, surrounding the NS. This scenario corresponds to the AXP. Accretion onto the thermal surface and the occasional release of thermal energy are responsible for the X-ray emission and variabilities. The remnant formed via explosion of TZO has a denser crust and a core similar to a canonical NS, accreting from a fallback disk. It is the accretion onto the denser surface that contributes to the harder X-ray spectra in the case of SGRs. We expect that the repeated soft γ-ray emission and bright outbursts are related to the reconstruction of dynamic equilibrium after the clumpy accumulation of accreted material onto the denser surface.

However, due to the strict condition for origin of SGR/AXP via this mechanism, the birth rate of SGR/AXP is lower than 6 per millenium in galactic field. However, if the system is located in a massive star cluster, the birth rate should be enhanced, and the remnants are expected to be associated with supernova remnants.

If SGR/AXP is in massive clusters, the passing of field stars will perturb the system. On one hand, the perturbation will produce inhomogeneities and clumps in a fallback disk. An inhomogeneous accretion and a strike of accreted clumps onto the denser surface may result in a sudden enhancement of luminosity and gradual release of thermal energy, manifesting as giant flares. On the other hand, the perturbation of passing field stars can lead to the ejection of some fragments and therefore prograde or retrograde angular momentum of a debris disk. The prograde or retrograde angular momentum imposes an impact on the central NS, presenting glitch or anti-glitch. The change of angular momentum also is responsible for an enhancement of accretion rate, manifesting as outbursts.

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