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Research Article

Can SGRs/AXPs Originate from Neutron Star Binaries?

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Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are two groups of enigmatic objects, which have been extensively investigated in past few decades. Based on the ample information about their timing behaviors, spectra, and variability properties, it was proposed that SGRs/AXPs are isolated neutron stars (NSs) with extremely strong magnetic fields, the so-called magnetars. Nonetheless, some alternative models are probably equally convincing such as those proposing that they are accreting NSs with a fall-back disk or rotation-powered magnetized and massive white dwarfs. The nature and nurture of SGRs/AXPs remain controversial. In this paper, we propose that SGRs/AXPs can, alternatively, originate from normal NSs in binary systems, which resorts to the reexplosion of normal NS induced by instant contraction of the massive star envelope in a Thorne-Żytkow object (TZO). The spin-period clustering is due to either the brake of a slowly rotating envelope or the frictional drag during the common-envelope phase.

1. Introduction

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are an exotic population of X-ray pulsars, very different from radio pulsars and normal X-ray pulsars produced by typical core-collapse of massive stars [1, 2]. All the SGRs and AXPs appear to be young and radio-quiet objects with spin periods clustered in the range from period $P = 5\,\text{s}$ to $12\,\text{s}$. Their spin-down rate is relatively steady with a characteristic timescale of $P/\dot{P} = 10^3$–10^5 yrs. SGRs, characterized by their short, repeating bursts of soft gamma-ray radiation (see [3] for a review), are detected through their brilliant flashes of X-rays and gamma-rays (e.g., [4]). They have been identified with persistent X-ray sources with hard X-ray flares (see [2] for a review). AXPs emit soft X-ray spectra with constant luminosity at $L_X \sim 10^{34}$–10^{36} ergs/s, which is 2-3 orders higher than their spin-down luminosity ($\dot{E}_{\text{rot}} \sim 10^{32}$–$10^{33}$ ergs/s, [5]). There is no evidence for AXPs with massive companion stars. SGRs/AXPs share some similarities with each other in a three-dimensional parameter space (i.e., P, $\dot{P}$, and L_X; for detailed reviews, see [1, 2]).

The standard model of SGRs/AXPs involves highly magnetized neutron stars (NSs) magnetars [6, 7]. The Thompson cross section is strongly reduced in a very strong magnetic field and the luminosity is enhanced, which can explain the super-Eddington luminosity in the March 5, 1979, event [6]. According to the idea that the magnetic dipole braking comes at the cost of rotational energy loss in the frame of classical electrodynamics, spin periods of a few seconds with spin-down age of 10^3–10^5 yrs also infer a magnetic field beyond the quantum critical value of $B_c = 4.4 \times 10^{13}$ G [7]. Therefore, the very strong magnetic field ($\sim 10^{14}$–10^{15} G), originating from turbulent dynamo amplification [8] of fossil fields, causes the spin-down and powers the variable X-ray emission through magnetic dipole radiation and/or a magnetically powered relativistic wind [9–11].

It seems that the "magnetar" model can successfully explain the observations of SGRs/AXPs, especially the intense bursts. There are, however, some alternative models which are also able to interpret the properties of SGRs/AXPs successfully to a considerable extent. Although the X-ray luminosity of SGRs/AXPs is much higher than their spin-down energy loss rate, a rotation-powered massive white dwarf (WD) with a high magnetic field ($\sim 10^8$ G) and rapid rotation, formed by merger of two ordinary WDs, can provide the energy of X-ray emission and manifest itself as a 7-s periodicity X-ray pulsar, such as 1E 2259 + 586, through the loss of its rotational energy [12–14]. Several proposals ascribe the properties of AXPs and, to a less extent of SGRs, to the accretion mechanism from residual disks, without introducing particularly high magnetic fields. In this class of models, different mechanisms for disk formations and different origins of the observed X-ray luminosity are considered. Despite the lack of substantial shift of X-ray pulse arrival times and the absence of optical counterparts, which indicate that there are no massive companion stars [15], it cannot be excluded that the X-ray flux is powered by accretion, which can originate from a binary with very low mass companion [16], a debris disk of a disrupted massive companion [15, 17], or a disk formed by the fallback matter after a supernova (SN) explosion [18–21]. All these models can better explain the clustering of spin periods observed for AXPs [22]. A fall-back disk is supported by the IR/optical radiations from both 4U 0142 + 61 [23] and 1E 2259 + 586 [24]. In addition, regarding the nature of SGRs/AXPs, some models suggest that they are made of more elementary matters instead of NSs. Quark-star models were proposed as a manifestation of pulsar-like SGRs/AXPs on the ground of quark matter as the most stable configuration for dense compact stars [25, 26]. A P-star model for stars made of up and down quarks, which still involves super-strong dipolar fields, was also proposed [27].

Because of some new observations and fundamental questions, the nature and nurture of SGRs/AXPs are still the matters of debate. Firstly, the strong magnetic field is estimated based on the assumption that the spin-down is due to magnetic dipole braking in the framework of classical electrodynamics. However, one may ask whether an ultrastrong magnetic field beyond the quantum critical value can be estimated according to classical electrodynamics or not. In addition, the fact that no significant detection is reported in Fermi observations, reflects that different physical conditions may present for the magnetosphere of magnetars. It was claimed that the magnetars are NSs with strong multipole fields (e.g., [28]). As a result, whether the spin-down of magnetars is dipole or multiple spin-down needs further investigation. Therefore, it is questionable for the reliability of 10^{14}–10^{15} G strong dipole fields estimated from the equation

$$B_{\text{dipole}} = 3.2 \times 10^{19} \sqrt{P\dot{P}}\, G. \quad (1)$$

Secondly, according to (1), several SGRs/AXPs with relatively low surface magnetic fields ($B_s < B_c$) were detected (e.g., [29, 30]; see McGill SGR/AXP online "http://www.physics.mcgill.ca/~pulsar/magnetar/main.html" for an updated catalogue). There are some radio pulsars which show high surface magnetic fields ($B_s > B_c$) and SGR/AXP-like bursts (e.g., [31, 32]; see also [33, 34] for reviews). Moreover, radio emission was observed in some AXPs, such as XTE 1810-197 [35] and 1E 1547.0-5408 [36]. These detections indicate that the difference between radio pulsars and SGRs/AXPs is not rooted in the magnetic-field strength. In addition, although soft X-ray spectra of SGRs/AXPs do not correspond to canonical accreting systems and there are no significant Doppler shifts in pulse arrival times of AXPs (e.g., [37–39]), by which the existence of a massive companion is excluded, the scenario that they are a special kind of accreting objects remains possible. The discovery of X-ray source 4U 2206 + 54 with very slow pulsations ($P = 5560$ s) resulted in the proposal of accreting magnetars [40].

Understanding SGRs/AXPs involves the issues of both the object's internal nature and their exterior environment, which together cause their exotic properties. In this paper we investigate the natal conditions and processes of SGRs/AXPs. We propose that SGRs/AXPs can be reborn objects distinct from normal NSs, originated by either coalescence or catastrophic collision between a normal NS and its noncompact companion in binaries. We claim that they can alternatively come from the reexplosion of normal NSs induced by the instant contraction of the massive star envelope in a Thorne-Żytkow object (TZO). We describe the possibilities of SGRs/AXPs as reborn NSs originating from binary systems in Section 2. In Section 3, we study the scenarios in high mass NS binary systems (HMNBs hereafter), in which different physical processes for different companion masses are presented. A possible mechanism for the formation of AXPs in low mass NS binaries (LMNBs hereafter) is investigated in Section 4. We also discuss the results of direct star-star collision in Sections 5 and 6. Section 7 contains conclusions.

2. Can SGR/AXP Be Formed from NS Binaries?

In general, the generation of pulsed radio and X-ray emission of NSs can be ascribed to several mechanisms. Loss of rotational energy and magnetic energy can be the power of normal pulsars and strongly magnetized NSs, respectively. Although there is no evidence that SGRs/AXPs have optical companions, some facts support the idea that their X-ray emissions are powered by accretion [16, 41]. However, the softer X-ray spectra in SGRs/AXPs and the less luminous X-ray flux without secular variation conflict with properties of canonical binaries. Particularly, the extremely soft power-law spectrum of 4U 0142 + 61 [42] led to an initial classification of a black hole candidate.

It is well known that a normal NS can accrete matter from its optical companion at the mean Eddington accretion rate, via either wind or disk accretion. Wind-fed systems always occur in HMNBs and result in a normal X-ray pulsar, while a disk-fed one often involves LMNBs and leads to recycled pulsars. If, in some certain systems, the NS is swallowed by its companion and merged due to expansion of the companion, or the NS coalesces with another star because of catastrophic encounter, what is the destiny of the NS and the system?

An NS in high mass X-ray binaries (HMXBs) is usually a wind-fed object with a massive optical companion in rapid evolution. The evolution of the massive normal star can make it engulf the NS, forming a common envelope (CE). The outcome of the CE phase depends mainly on the orbital period (P_{orb}) at the onset of this phase (e.g., [43, 44]). A relatively wide orbit with $P_{\mathrm{orb}} > P_{\mathrm{min}}$ (see [45] for the calculation of the minimum critical period P_{min}) can release sufficient orbital energy and lead to the complete expulsion of the massive envelope before the NS settling at its core, leaving a tight binary system containing an NS and a Helium companion. For $P_{\mathrm{orb}} < P_{\mathrm{min}}$, the NS spirals in to the center of the massive companion, forming a TZO [46, 47]. The subsequent evolution is expected to produce a new object distinguishable from normal NSs.

If an NS with a very low mass companion (e.g., $\leqslant 0.5\,M_{\odot}$, [48]) is located in a highly compact binary with an ultrashort orbital period, an orbital decay is expected to be significant due to the energy release by means of gravitational radiation. In addition, tidal oscillation may deposit thermalized tidal energy in the companion [49, 50]. Consequently, the high tidal luminosity leads to an expansion and overflow from the Roche lobe (RL), which also contributes to the spiral-in of the NS and then the merger. If the binary system is located in a globular cluster, an encounter between the binary and a single star may drive the binary components moving closer to each other more rapidly [51] and subsequently mass transfer is enhanced [52]. As a result, the comparable increase in viscosity following the intense mass transfer leads to a much higher accretion rate. The intense mass accretion to the NS may be responsible for a coalescence of the companion star. On the other hand, a directly physical star-star collision, as the results of encounter or asymmetric kick velocity of a newborn NS, can also result in a coalescence and merger between the NS and the encountered star. We expect that the merger of NS-star leaves an exotic object.

3. Formation of SGRs/AXPs in HMNBs

3.1. Possible Fate of HMNBs. We consider only those binary systems in which the RL overflow (RLOF) transfers matter from the massive companion to the NS, at a super-Eddington rate. According to different evolutionary tracks and properties, these systems may evolve into distinct destinies. Firstly, because of a considerably super-Eddington mass transfer ($\sim 10^{-3}$–$10^{-5}\,M_{\odot}$/yr), the NS may be unable to accrete most of the material from the companion. The material accreted into the RL of NS does not fill up the lobe to form a CE. It instead squirts out by way of bipolar relativistic jets. As a result, the whole envelope is ejected, without obvious orbital reduction. However, the above process happens only in certain systems with some specific properties (e.g., [53]). In the second place, a CE is formed when the massive star evolves into a supergiant with central helium burning [54]. After considerable spiral-in because of gas drag, the CE is ejected before coalescence, forming a close binary or even a double NS binary.

There is another important outcome during the evolution of the CE phase in which orbital decay is involved, due to the angular momentum transportation by the convection in the envelope. The NS finally spirals in towards the center and completes coalescence to form a TZO [43, 46, 47, 55]. A typical TZO consists of three regions [47], that is, a convection envelope, a radiative and approximate isothermal halo, and an NS core.

In the structure like a TZO, the inflows from the envelope accreted onto the NS core through the halo release gravitational energy, and the nuclear burning at the base of convection envelope produces nuclear energy [56–59]. Both of the two kinds of energy manifest themselves as stellar luminosity L_X. Therefore, the X-ray luminosity of the TZO-like structures consists of two parts:

$$L_X = L_N + L_G, \tag{2}$$

where L_N denotes the luminosity converted via nuclear burning and L_G is provided by loss of gravitational energy.

Based on the mass of envelope and the central energy source [60], the TZOs fall into two classes: "giant" models with a low mass envelope ($\leqslant 8\,M_{\odot}$) and "supergiant" models with a massive envelope ($\geqslant 10.5\,M_{\odot}$). The "giant" model is dominated by the gravitational energy (accounting for about 97%) released by means of accretion at Eddington rate, with the other 3% of energy from nuclear burning. For the "supergiant" models, about 95% of their energy comes from nuclear burning by means of rapid proton processes (rp-process, [56]), and the gravitational energy only accounts for 5%.

3.2. Physics in "Giant" Models. If the total mass of a TZO is less than $9\,M_{\odot}$, which corresponds to the "giant" model, the squeeze of the stellar envelope cannot significantly influence the hydrostatic structure of the NS core [47]. The NS core accretes material from the inner region of a massive envelope. For the systems with total mass of less than $5\,M_{\odot}$, there is no envelope [47], and the NS core accretes matter from the halo.

Because of the inefficiency of convection in the inflowing envelope, the mass flows from the envelope into the radiative-dominant halo and the NS core, releasing gravitational energy. Part of the released gravitational energy converts into X-ray luminosity, and the other part heats the inflows. In addition, the inflowing material is heated by absorbing part of the outgoing luminosity. As a result, a considerable gravitational energy of the inflows deposits as thermal energy near the NS core.

Between the neutron-drip core and halo, the accreted material becomes electron degenerate matter, forming a thin "insulating layer" (with the range of temperature in 10^8–10^{10} K), which isolates the core. In this layer, the inflows release the deposited heat at a rate of about 10^{35} ergs/s [47] via nuclear burning, carried away by electron conductivity and neutrino runaway. On the other hand, if the NS core is mildly more massive than $1.4\,M_{\odot}$ with a somewhat smaller radius and therefore a higher density, the nuclear burning is less efficient (see Tables 3 and 4 in [47] for numerical details). In addition, a temperature higher than 10^9 K will also trigger substantial neutrino losses. Therefore, the stronger neutrino runaway may couple with the runaway temperature and accretion rate, leading to the catastrophic contraction of a TZO structure and the ejection of the envelope. As a result, the NS core is accreting material from the remnant disk, emitting X-rays in the quiescent state. Because of the instant catastrophic contraction, the thermal energy in the halo and the insulating layer cannot be released efficiently and deposits near the contracted core. The huge deposited thermal energy occasionally releases, manifesting as the variabilities and timing behaviors like that in SGRs/AXPs.

3.3. Mechanisms in "Supergiant" Models. The systems which have a total mass larger than $11.5\,M_\odot$ are referred to as the "supergiant" TZO models. The more massive envelope contributes to the convective heat transport [60]. The convective envelope dips into the hydrogen-burning shell, in which most energy is produced by the rp-process [56]. Therefore, the energy source of a supergiant TZO is the nuclear burning energy via the rp-process [57, 58]. In order to support the more massive weight (especially for an envelope mass $\geqslant 14\,M_\odot$, [59]) above the core, a great number of electron-positron pairs are generated near the core, leading to the increase of opacity and the reduction of release of gravitational energy by a factor of 10–100 [47]. On the other hand, the nuclear burning near the core requires continual injection of fresh fuel, forming a hot region of fuel reservoir [59].

After exhausting the rp-process seed elements in the envelope [56], the steady nuclear burning will terminate. If 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 can reach a denser region with higher pressure and temperature, which may lead to the change of its equation of state. When the gravitational potential of the NS core cannot support the higher pressure and density, the collapsed TZO structure reexplodes and ejects part of the material in the envelope, leaving a reborn object. Because the exhaustion of the light elements in the primordial TZO structure only happens in the massive envelope, the core remains in the state of neutron drip. The expected effect of reexplosion is to change the state of crust of the original NS, producing a crust with a stiffer equation of state. As a result, the reborn object should contain a neutron-drip core and a denser crust with a stiffer equation of state, accreting from a disk formed by fallback material.

On the other hand, if the mass of the envelope decreases to be below the minimum mass for nuclear burning via intense stellar wind [59], the supply of fresh fuel is choked off and a radiative region develops. The system taps the huge store of gravitational energy by means of nonsteady accretion from the halo onto the NS core. Due to the enhanced opacity by the electron-positron pairs and the runaway neutrino losses near the core [47], the X-ray luminosity is reduced to about one or two orders lower than the Eddington luminosity [59]. In addition, the region above the core efficiently runs out of the reserved fresh fuel and heats up. The runaway neutrino loss ultimately becomes the dominant energy-loss mechanism. Consequently, the accretion onto the NS core is at a sub-Eddington rate of $\sim 10^{-10}\,M_\odot$ [59]. Finally, most of the envelope contracts and forms a massive disk-like structure around the NS core.

4. Formation of SGRs/AXPs in LMNBs

4.1. Gravitational Radiation. It is recognized that binary systems are possible radiators of gravitational waves [61]. Gravitational radiation may significantly influence the evolution in a moderate or low mass binary system. This effect, however, only dominates in the lowest mass binaries [62], with a companion mass of about $\leqslant 0.5\,M_\odot$ [48] and an ultrashort orbital period [63]. In close binary systems with a magnetized NS, gravitational radiation can lead to two effects. (1) If the companion is a low mass white dwarf [64] or an RL-filled star (e.g., [65]), mass transfer from the companion to the NS may occur. (2) When the companion star has not filled in its RL, gravitational radiation only removes energy and angular momentum [63]. As a result, the physical scale will always decrease for a mass conservative binary.

We consider a close binary containing a newborn NS (M_N) and a low mass companion (M_C) without filling the RL. We assume that the system has orbital separation a and angular velocity ω and that the system mass is conserved. Therefore, the total mechanical energy is $E = -G(M_N M_C/2a)$. According to Landau and Lifshitz [61], the rate of energy loss is given by

$$\dot{E} = -\frac{32}{5}\left(\frac{M_N M_C}{M_N + M_C}\right)^2 a^4 \omega^6. \tag{3}$$

Assuming a circular orbit, we get the expression for the rate of orbital decay [48]

$$\dot{P}_{\mathrm{orb}} \sim 10^{-49} \frac{M_N M_C}{\left(M_N + M_C\right)^{1/3}} P^{-5/3} \mathrm{yrs}^{-1}, \tag{4}$$

according to the Keplerian law $\omega^2 a^3 = G(M_N + M_C)$. Consequently, the two components contact at a timescale of

$$\tau \sim 10^{-3} \frac{\left(M_N + M_C\right)^{1/3}}{M_N M_C} P^{8/3} \mathrm{yrs}. \tag{5}$$

We assume that SGR/AXP can be formed from a low mass binary which experiences initial gravitational radiation. Considering the typical age of 10^3–10^5 yrs for SGRs/AXPs, the original binary system, comprising a $1.4\,M_\odot$ NS and a $\leqslant 0.5\,M_\odot$ companion star, should have an orbital period of about 2–20 mins. Therefore, the systems with such properties can be expected to coalesce via gravitational radiation and form magnetar-like objects.

4.2. Tidal Interaction. The tidal capture mechanism [49] plays a favored role in close binaries. An optical companion star can excite nonradial oscillations via tidal impulse, which deposits an amount of tidal energy by means of oscillatory modes [50]. The deposited oscillatory energy will be released as tidal luminosity, by means of viscous dissipations. As a result, the original equilibrium configuration is disturbed. The optical star attempts to achieve a new equilibrium configuration, which leads to the expansion of its radius up to 10 times larger than that of the original star [66]. For a close binary system experiencing the orbital decay by means of gravitational radiation, the expanded companion will engulf the NS, forming a CE.

4.3. Fate of Contacted Components. There are two effects of energy dissipation in the CE. Firstly, the tidal energy dissipates by means of viscosity, which generates luminosity of L_{tid}. For a typical main sequence star with a mass of $0.6\,M_\odot$, the accumulated tidal energy can release and emit luminosity of $\sim 10^{42}$ ergs/s during a viscous timescale of $\tau_{\text{vis}} \sim 10^{3-4}$ yrs. Secondly, the frictional drag between the CE and the NS also results in the dissipation of orbital energy at a rate of $\dot{E} = \pi\rho(GM_N)^2\sqrt{G(M_N + M_C)/R_{\text{orb}}}$ [66], where ρ is the density of the CE and R_{orb} is the orbital separation between the NS and the dense core of the companion star. We assume that the NS velocity relative to the CE (v_{rel}) is far larger than the sound speed ($c_s \ll v_{\text{rel}}$) and that there is no loss of mass and angular momentum in the system. If the timescale of orbital energy dissipation τ_{orb} is shorter than the viscous timescale τ_{vis} ($\tau_{\text{orb}} < \tau_{\text{vis}}$), a significant spiral-in of the NS is expected. Consequently, the NS coalesces into the dense core, leaving a massive disk around it. The deposited tidal energy ($\sim GM_C M_N/R_{\text{orb}} \sim 10^{48}$ ergs) in the massive disk will occasionally cause the emission of X-rays, which accounts for the variable properties of AXPs.

5. Encounter with Single Stars

In globular clusters (GC), binary systems occasionally encounter passing field stars, which may have considerable influence on the evolution of the system [67]. The expected mean effect of gravitational perturbations by field stars on a highly compact binary system is to change the original orbital parameters and drive the two components into tightly bound orbits [51]. The interaction between binaries and field stars can be either distant or catastrophic encounters.

Distant encounters occur when a single star passes the binary from a large distance. In such a case, the orbital parameters will change only by a small amount [68], and the semimajor axis is hardly affected [69]. The change in the orbital angular momentum J is manifested by the change of orbital eccentricity e, with $\delta J^2 \propto \delta(1 - e^2)$ [52]. The tidal dissipation causes rapid orbital circularization and rotational synchronization, which shrinks the orbit on a short timescale [51]. During the encounters, mass will transfer from the low mass companion star to the NS. The perturbation of passing field stars will strongly enhance the rate of mass transfer, resulting in a super-Eddington accretion. This can destroy the binary and drive the system into a CE phase [52]. With further spiral-in of the NS towards the center, a system in which an NS accretes from a massive disk forms. However, because the accretion is steady without intense variation, the variability of AXPs is not expected in this scenario.

Those encounters which may suffer rapid mass transfer and finally destroy the binary are defined as catastrophic encounters, in which three scenarios were developed (see [51] for details). We only consider direct collision between the NS and the field star, assuming the collision is inelastic. Because of the high velocity of stars in clusters, the collision is catastrophic, which leads to the coalescence of two objects, that is, the NS embedding into the field star. Consequently, an instant and intense mass transfer from the field star to the NS occurs in the coalesced system. Due to the rapid process of mass transfer, much of matter from the field star will remain bound to the NS. This process disrupts the field star and the subsequent dynamics is expected to be violent. Because of the rapid deposit of matter and striking energy, the NS crust cannot keep its original properties, and the system reexplodes. As a result, a reborn object with the original NS core and a denser crust comes into being, accreting from a thin disk formed by the fallback matter. On the other hand, if the direct star-star collision only involves the companion star in the original binary, the rapid mass transfer may leave a massive and nonequilibrium disk (up to $0.1\,M_\odot$, [51, 70]) around the NS [52].

6. Recollapse of a Newborn NS

It is widely believed that an NS formed by SN explosion gains a large kick velocity. In a dense GC or a tight binary system, when a more massive star explodes as SN, the newborn NS can be given an asymmetric kick velocity and run into another star to become embedded in that star [71]. If the embedding star is a massive main sequence star ($\geqslant 10\,M_\odot$, [72]), the NS spirals in directly towards the core due to the frictional drag between the NS and the embedding star. Consequently, the NS enters into the core of the embedding star, and the two components form a TZO with a massive envelope. Then, if super-Eddington accretion occurs, both the instantly huge accumulation of material and a runaway accretion onto the NS core will inevitably follow. The instant accumulation of accreted matter may lead to the recollapse of the original NS core and finally leaves a magnetar-like object.

7. Summary and Discussion

Based on the recent challenges to the magnetar model and the possibility that AXPs can be accreting objects, we investigate several scenarios in which SGRs/AXPs are born in normal NS binary systems. We suggest that SGRs/AXPs can be reborn objects from normal NSs with distinct physical properties. The formation of magnetar-like objects begins with the coalescence between a normal NS and the optical companion star, which can occur in close NS binary systems with both high mass companion star and low mass companions, as well as in the catastrophic encounters in GC. After coalescence, the NS will spiral in towards the center of the embedded massive star, forming a TZO. The subsequent evolutions are different in distinct physical conditions, with different masses of embedded stars. We present several possible scenarios according to distinct physics. As a result, because of the deposit of energy near NS and the exhaustion of energy in the massive star envelope, the contraction of massive envelope in TZO occurs, which contributes to a reexplosion of the contracted system due to huge energy accumulated near the NS. It is the reexplosion that produces the magnetar-like object, which involves an NS core and denser crust, with a fallback disk.

If the embedded star is a very massive star like that in high mass NS binary systems, it is, generally, expected to form a black hole. However, most of mass in a TZO is distributed in the massive envelope and just with a ~1.4 $M_\odot$ core. Because of the transport of energy from outer to inner layer and deposit nearly above the NS core, a huge amount of thermal energy accumulates around the NS when the contraction of massive envelope occurs. If the deposited thermal energy cannot balance the squeeze of contracted massive envelope, the system will reexplode. As a result, most of the contracted envelope above the energy layer is blown up, with a part of material fallback and forming a thin disk. Therefore, the remained object cannot be massive enough to leave a black hole, but a magnetar-like object.

SGRs/AXPs are characterized by high spin-down rates and spin clustering with long periods. The change of spin periods, in an accreting system, obviously resorts to the transport of angular momentum by accreted matter. If the SGRs/AXPs formed in systems with an NS core accreting from a massive envelope, which corresponds to the scenarios in HMNBs (see Section 3) and recollapse of a newborn NS (see Section 6), most of the material in the envelope falling onto the NS core on a dynamical timescale is expected to have less angular momentum than the maximum angular momentum allowed for a normal NS, due to the neutrino runaway. It is estimated that the angular momentum of the envelope for a typical TZO is $J_{\rm env} \sim 10^{53} P_{10,d}^{1/3}\,{\rm g\,cm^2\,s^{-1}}$, where $P_{10,d}$ is the initial orbital period of an HMNB in units of 10 days. Assuming a moment of inertia of $I_{\rm env} \approx 10^{61}\,{\rm g\,cm^2}$ for the envelope, the angular velocity is $\omega_{\rm env} \sim 10^{-9} P_{10,d}^{1/3}\,{\rm s^{-1}}$, which is much less than the break-up angular velocity ($\omega_{\rm max} \sim 5 \times 10^{-8}\,{\rm s^{-1}}$) at the surface of a typical TZO. Therefore, the envelope of a TZO is a slow rotator relative to the NS core. When accreting matter from the slowly rotating envelope at a sub-Eddington rate, the NS core will be spun down [59]. For an NS with mass of $M_N = 1.4\,M_\odot$, radius of $R_N = 10^6$ cm, and moment of inertia of $I_N \approx 10^{45}\,{\rm g\,cm^2}$, the total mass directly accreted can spin down the NS to two orders lower. In addition, because the reexplosion/recollapse of the original NS has influence merely on the equation of state of its crust, we do not expect this process can significantly spin up the NS. After the formation of the accreting sources, high spin-down rates can be expected to arise in the propeller phase (see, e.g., [17]).

If SGRs/AXPs are formed in LMNBs or by means of encounters with field stars in a GC, the NS in a CE cannot be significantly braked by the slowly rotating massive envelope. When the low mass companion expands and swallows the NS due to tidal oscillation, the tidal energy deposits near the original NS core by means of different oscillatory modes after the NS spiraling into the dense core, thanks to a short viscous timescale. If the SGRs/AXPs come into being via encounters with field stars in GC, the huge striking energy coming from the inelastic collision is also accumulated as thermal energy. Consequently, there will be energy dissipation due to frictional heating during the accretion phase, which releases as thermal luminosity and leads to the spin-down of the NS. We assume that the NS accretes from a disk with moment of inertia $I_{\rm cru}$ and angular velocity $\omega_{\rm cru}$. The rate of energy dissipation can be given by $\dot{E}_{\rm dis} \sim I_c \omega_c |\dot{P}_s| / P_s^2$ [73], where P_s is the NS spin period. For a crust with mass of $M_{\rm cru} \geqslant 0.1\,M_\odot$ and radius of 100 km–1000 km, the expected upper and lower limit of spin-down rate is $10^{47}|\dot{P}_s|$ ergs/s $< \dot{E}_{\rm dis} < 10^{50}|\dot{P}_s|$ ergs/s, that is, $|\dot{P}_s| \sim 10^{-13}$–$10^{-10}\,{\rm s^{-1}}$.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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