Can SGRs/AXPs originate from neutron star binaries?

Jing Wang¹ *, Hsiang-Kuang Chang¹,²
¹ Institute of Astronomy, National Tsing Hua University, Hsinchu 30013, Taiwan
² Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan

Received date ; accepted date

ABSTRACT
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 originate from normal NSs in binary systems. SGRs are a class of objects containing a neutron-drip core and denser crust with a stiffer equation of state, which is formed from re-explosion of normal NSs in binary systems. It is the accretion onto the denser crust that contributes to the observed hard emissions. AXPs are a group of NSs which reserve huge thermal energy in an insulating layer above the surface. This structure accretes material from a massive disk, manifesting themselves via release of deposited energy. The spin-period clustering is due to either the brake of a slowly rotating envelope or the frictional drag during the common-envelope phase.

Key words: stars: neutron – stars: magnetic – stars: binaries.

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 (Woods & Thompson 2006; Mereghetti 2008). All the SGRs and AXPs appear to be young and radio-quiet objects with spin periods clustered in the range from period $P = 5$ s to 12 s. Their spin-down rate is relatively steady with a characteristic timescale of $P/\dot{P} = 10^3 - 10^4$ yrs. SGRs, characterized by their short, repeating bursts of soft gamma-ray radiation (see Hurley 2000 for a review), are detected through their brilliant flashes of X-rays and gamma-rays (e.g. Mazets et al. 1979). They have been identified with persistent X-ray flares (see Mereghetti 2008 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 ($E_{\text{rot}} \sim 10^{32} - 10^{33}$ ergs/s, Mereghetti 2002). There is no evidence for AXPs with massive companion stars. These two classes of objects share some similarities with each other in a three-dimensional parameter space (i.e. $P$, $\dot{P}$, and $L_X$; for detailed reviews, see Woods & Thompson 2006; Mereghetti 2008). Generally speaking, SGRs, with spin periods of 5-8 s, have somewhat smaller characteristic ages than AXPs, whose spin periods are in the range of 6-12 s.

The standard model of SGRs/AXPs involves highly magnetized neutron stars (NSs) – magnetars (Paczynski 1992; Duncan & Thompson 1992). 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 5th, 1979 event (Paczynski 1992). 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 (Duncan & Thompson 1992). Therefore, the very strong magnetic field ($\sim 10^{14} - 10^{15}$ G), originating from turbulent dynamo amplification (Thompson & Duncan 1993) 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 (Thompson & Duncan 1995, 1996; Thompson et al. 2002).

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 (Morini et al. 1988; Paczyński 1990; Malheiro, Rueda & Ruffini 2012). 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 (van Paradijs, Taam, & van den Heuvel 1995), it cannot be excluded that the X-ray flux is powered by accretion, which can originate from a binary with very low mass companion (Mereghetti & Stella 1995), a debris disk of a disrupted massive companion (van Paradijs et al. 1995; Ghosh, Angellini & White 1997), or a disk formed by the fallback matter after a supernova (SN) explosion (Corbet et al. 1995; Chatterjee, Hernquist & Narayan 2000; Alpar 2001; Marsden et al. 2001). All these models can better explain the clustering of spin periods observed for AXPs (Chatterjee & Hernquist 2000). A fall-back disk is supported by the IR/optical radiations from both 4U 0142+61 (Wang et al. 2006) and 1E 2259+586 (Kaplan et al. 2009). 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 (Xu 2007; Horvath 2007). A P-star model for stars made of up and down quarks, which still involves super-strong dipolar fields, was also proposed (Cea 2006).

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 ultra-strong magnetic field beyond the quantum critical value can be estimated according to classical electrodynamics or not. If the answer is positive, then whether the state of matter in the crust of NSs and the radiation mechanisms in such a strong magnetic field are similar to that of the normal pulsars or not. Especially, the fact that no significant detection is reported in Fermi observations leads to the idea that the magnetars are NSs with strong multipole fields (e.g. Tong et al. 2012), which challenges the dipole braking assumption. Therefore, it is questionable regarding the reliability of $10^{14} - 10^{15}$ G strong dipole fields estimated from the equation

$$B_{dipole} = 3.2 \times 10^{13} \sqrt{\frac{P}{P_G}}.$$  \hspace{1cm} (1)

Secondly, according to Eq. 1 several SGRs/AXPs with relatively low surface magnetic fields ($B_s < B_c$) were detected (e.g. Rea et al. 2010, 2012; 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. Camilo et al. 2000; Gotthelf et al. 2000; see also Manchester et al. 2005 for a review). Moreover, radio emission was observed in some AXPs, such as XTE 1810-197 (Camilo et al. 2006) and 1E 1547.0-5408 (Camilo et al. 2007). These detections indicate that the difference between radio pulsars and SGRs/AXPs is not rooted in the magnetic-field strength. In addition, PSR J1852+0400, a compact central object (CCO) in the supernova remnant (SNR) Kes 79, shows a low field of $3.3 \times 10^{10}$ G but with $L_{\nu} > E_{\nu, \text{rot}}$ (Halpern & Gotthelf 2010). Hence a super-strong magnetic field does not seem to be necessary and sufficient for the appearance and emission of SGRs/AXPs. Thirdly, 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. Koyama et al. 1989; Corbet & Day 1990; Israel, Mereghetti, & Stella 1994), 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 (Reig, Torrejón & Blay 2012).

To understand 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 and 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 non-compact companion in binaries. SGRs are the reborn objects containing a neutron-drip core and a denser crust with a stiffer equation of state, which comes from the re-explosion of normal NSs. The re-explosion can be induced by the instant contraction of the massive star envelope in a Thorne-Żytkow object (TZO). It is the accretion onto the denser crust that contributes to the observed hard emissions. While AXPs are the reborn NSs with reserved huge thermal energy in an insulating layer above the surface. This structure accretes material from a massive disk and occasionally releases deposited energy, manifesting the X-ray variabilities. We describe the possibilities of SGRs/AXPs as born 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 section 5 and section 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 (Baykal & Ögelman 1995; Mereghetti & Stella 1995). 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. Especially, the extremely soft power-law spectrum of 4U 0142+61 (White et al. 1987) 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 results 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 ($P_{\text{orb}}$) at the onset of this phase (e.g. Taam, Bodenheimer & Ostriker 1978; van den Heuvel 1989). A relatively wide orbit with $P_{\text{orb}} > P_{\text{min}}$ (see Taam 1996 for the calculation of the minimum critical period $P_{\text{min}}$) 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 $P_{\text{orb}} < P_{\text{min}}$, the NS spirals in to the center of the massive companion, forming a TZO (Thorne & Zytkow 1975, 1977). 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. $\lesssim 0.5 M_\odot$, Paczyński 1967) is located in a highly compact binary with an ultra-short 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 (Fabian, Pringle & Rees 1975; Press & Teukolsky 1977). 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 (Koliuk, Meiksin & Joss 1984) and subsequently mass transfer is enhanced (Hut & Paczyński 1984). 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 coalesce of the companion star. On the other hand, a directly physical star-star collision, as the result 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 HMXNs

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. Fabian et al. 1986). In the second place, a CE is formed when the massive star evolves into a supergiant with central helium burning (Flannery & van den Heuvel 1975). 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 (Thorne & Zytkow 1975, 1977; Taam, Bodenheimer & Ostriker 1978; Taam 1979). A typical TZO consists of three regions (Thorne & Zytkow 1977), i.e. a convection envelope, a radiative and approximately 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 (Biehle 1991; Cannon et al. 1992; Cannon 1993; Podsiadlowski 1996). 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,

$$L_X = L_N + L_G,$$

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 (Eich et al. 1989), the TZOs fall into two classes: "giant" models with a low-mass envelope ($\lesssim 8 M_\odot$) and "supergiant" models with a massive envelope ($\gtrsim 10.5 M_\odot$). 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, Biehle 1991), 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 (Thorne & Zytkow 1977). The NS core accretes material from the inner region of a massive envelope. For the systems with total mass less than 5 $M_\odot$, there is no
envelope (Thorne & Żytkow 1977), 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 (Thorne & Żytkow 1977) 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 Table 3 and Table 4 in Thorne & Żytkow 1977 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 in AXPs.

### 3.3 Mechanisms in "supergiant" models

The systems which have a total mass larger than 11.5 $M_\odot$ are referred to the "supergiant" TZO models. The more massive envelope contributes to the convective heat transport (Eich et al. 1989). The convective envelope dips into the hydrogen-burning shell, in which most energy is produced by the rp-process (Biehle 1991). Therefore, the energy source of a supergiant TZO is the nuclear burning energy via the rp-process (Biehle 1991). The convective envelope contributes to the convective heat transport. Part of the released gravitational energy only happens in the massive envelope, the core remains in the state of neutron drip. The expected effect of re-explosion 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. It is the steady accretion from the fallback disk that contributes to the hard X-ray emission of the quiescent state in SGRs. Due to a denser crust, the accreted matter onto the surface may bring some intense emission, such as the observed burst behaviors of SGRs.

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. The system taps the huge store of gravitational energy by means of non-steady 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 (Thorne & Żytkow 1977), the X-ray luminosity is reduced to about one or two orders lower than the Eddington luminosity (Podsiadlowski 1996). 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 $\sim 10^{-10} M_\odot$ (Podsiadlowski 1996). Finally, most of the envelope contracts and forms a massive disk-like structure around the NS core, which is consistent with an AXP.

### 4 FORMATION OF SGRS/AXPS IN LMBNS

#### 4.1 Gravitational radiation

It is recognized that binary systems are possible radiators of gravitational waves (Landau & Lifshitz 1975). 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 (Webbink 1976), with a companion mass of about $\lesssim 0.5 M_\odot$ (Paczynski 1967) and an ultra-short orbital period (Faulkner 1971). 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 (Pringle & Webbink 1975) or an RL-filled star (e.g., Chau & Lauterborn 1977), 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 (Faulkner 1971). 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 $\omega$, and that the system mass is conserved. Therefore, the total mechanical energy is $E = -G M_N M_c/a$. According to Landau & Lifshitz (1975), the rate of energy loss is given by
\[
\dot{E} = -\frac{32}{5} \left( \frac{M_N M_C}{M_N + M_C} \right)^2 a^3 \omega^5.
\]
Assuming a circular orbit, we get the expression for the rate of orbital decay (Paczyński 1967)
\[
\dot{P}_{\text{orb}} \sim 10^{-49} \left( \frac{M_N M_C}{M_N + M_C} \right)^{17/8} P_{\text{orb}}^{-5/3} \text{ yrs}^{-1},
\]
according to the Keplerian law \( \omega^2 a^3 = G(M_N + M_C) \). Consequently, the two components contact at a timescale of
\[
\tau \sim 10^{-3} \left( \frac{M_N + M_C}{M_N M_C} \right)^{1/3} P_{\text{orb}}^{8/3} \text{ yrs}.
\]
We assume that SGR/AXP can be formed from a low mass binary which experiences initial gravitational radiation. Considering the typical age of \( 10^9 \sim 10^5 \) yrs for SGRs/AXPs, the original binary system, comprising a 1.4 \( M_{\odot} \) NS and a \( \leq 0.5 M_{\odot} \) companion star, should have an orbital period of about 2 - 20 mins. Then the two components in the system can coalesce via gravitational radiation.

### 4.2 Tidal interaction

The tidal capture mechanism (Fabian, Pringle & Rees 1975) plays a favored role in close binaries. An optical companion star can excite non-radial oscillations via tidal impulse, which deposits an amount of tidal energy by means of oscillatory modes (Press & Teukolsky 1977). 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 (Ray, Kembhavi & Antia 1987). 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 \( L_{\text{tid}} \). For a typical main sequence star with a mass of 0.6 \( M_{\odot} \), the accumulated tidal energy can be released and emit luminosity of \( \sim 10^{42} \) ergs/s during a viscous timescale of \( \tau_{\text{vis}} \sim 10^{2-3} \) yrs. Secondly, the frictional drag between the CE and the NS also results in the dissipation of orbital energy at a rate of \( \dot{E} = \pi \rho(GM_N)^2 \sqrt{G(M_N + M_C) \over R_{\text{orb}}} \) (Ray, Kembhavi & Antia 1987), where \( \rho \) is the density of the CE and \( R_{\text{orb}} \) 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 \( v_{\text{rel}} \), is the sound speed \( v_{\text{rel}} \), and that there is no loss of mass and angular momentum in the system. If the timescale of orbital energy dissipation \( \tau_{\text{orb}} \) is shorter than the viscous timescale \( \tau_{\text{vis}} \), 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 ENCOUCNTER 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 (Shull 1979). 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 (Krolik, Meiksin & Joss 1984). 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 (Hills 1975), and the semi-major axis is hardly affected (Heggie 1975). The change in the orbital angular momentum \( J \) is manifested by the change of orbital eccentricity \( e \), with \( \delta J^2 \propto \delta(1 - e^2) \) (Hut & Paczyński 1984). The tidal dissipation causes rapid orbital circularization and rotational synchronization, which shrinks the orbit on a short timescale (Krolik, Meiksin & Joss 1984). 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 (Hut & Paczyński 1984). 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 Krolik, Meiksin & Joss 1984 for details). We only consider direct collision between the NS and the field star, assuming the collision is inelastic. The collision results in an instant and intense mass transfer from the field star to the NS. 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 re-explodes. 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 non-equilibrium disk (up to 0.1 \( M_{\odot} \), Krolik, Meiksin & Joss 1984; Krolik 1984) around the NS (Hut & Paczyński 1984). The relevant X-ray luminosity during the quiescent state of SGRs/AXPs can be contributed by both scenarios. However, the object with the NS core and a denser crust is expected to be responsible for the variabilities in SGRs. Accretion from a massive, non-equilibrium disk may lead to occasional release of energy, manifested by less energetic and softer spectra, like those seen in AXPs.

### 6 RE-COLLAPSE OF A NEWBORN NS

It is widely believed that a 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 a SN, the newborn NS can be given an asymmetric kick velocity and run into another star to become embedded in that star (Leenard, Hills & Dewey 1994). If the embedding star is a massive main sequence star \((\geq 10 M_\odot)\), Dewey & Cordes (1987), 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 re-collapse of the original NS core, and finally leaves an object with an NS core and a denser crust, which corresponds to an SGR. If the runaway accretion is triggered, an intense neutrino runaway will be subsequently resulted in, which blows off part of the envelope and leaves an NS accreting from the massive disk. This is consistent with the scenario of AXPs.

7 DISCUSSIONS

7.1 Formation of spin change properties

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 4) and re-collapse of a newborn NS (see section 3), 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 \(J_{env} \sim 10^{53} P_{10,4}^{1/3} g \text{ cm}^2 \text{ s}^{-1}\), where \(P_{10,4}\) is the initial orbital period of an HMNB in units of 10 days. Assuming a moment of inertia of \(I_{env} \approx 10^{31} g \text{ cm}^2\) for the envelope, the angular velocity is \(\omega_{env} \sim 10^{-8} P_{10,4}^{1/3} \text{ s}^{-1}\), which is much less than the break-up angular velocity \((\omega_{max} \sim 5 \times 10^{-8} \text{ s}^{-1})\) 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 (Podsiadlowski 1996). For an NS with mass of \(M_N = 1.4 M_\odot\), radius of \(R_N = 10^6 \text{ cm}\), and moment of inertia of \(I_N \approx 10^{45} g \text{ cm}^2\), the total mass directly accreted can spin down the NS to two orders lower. In addition, because the re-explosion/re-collapse 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., Ghosh, Angelini & White 1997).

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 \(I_{cru}\) and angular velocity \(\omega_{cru}\). The rate of energy dissipation can be given by \(\dot{E}_{dis} \sim I_{cru} \dot{\omega}_{cru} |P_s|/P_{s}^{2}\) (Alpar et al. 1984), where \(P_s\) is the NS spin period. For a crust with mass of \(M_{cru} \geq 0.1 M_\odot\) and radius of 100 km - 1000 km, the expected upper and lower limit of spin-down rate is \(10^{47}|P_s| \text{ ergs/s} < \dot{E}_{dis} < 10^{39}|P_s| \text{ ergs/s}\), i.e. \(|P_s| \sim 10^{-13} - 10^{-10} \text{ s}^{-1}\).

7.2 Energy sources for X-ray emission

According to different formation mechanisms and different states of SGRs and AXPs, their X-ray emissions are from different energy sources in each scenario. An AXP formed in a binary system is an isolated NS with huge reserved thermal energy, mildly accreting from a massive disk. Therefore, the X-ray emission of AXPs is a result of the release of thermal energy during the accretion process, while SGRs involve the re-explosion or re-collapse of the original normal NS and a denser crust outside the neutron-drip core, so the X-ray luminosity and variabilities are related to the accretion onto a surface with a stiffer equation of state.

We expect the NSs located in HMNBs with less massive companions, which evolve into the "giant" TZOs, and in LMNBs can only coalesce and leave AXPs. The gravitational energy, which accounts for 97\% total energy, dominates the evolution of "giant" TZOs. A large fraction of that will be deposited above the NS core. According to Thorne & Zylkowski (1977), the accumulated gravitational energy is approximately \(10^4 L_\odot\). This gravitational energy converts into thermal energy and deposits above the reborn NS surface. As a result, the X-ray luminosity of \(10^{35} - 10^{36} \text{ ergs/s}\) comes from the release of thermal energy near the reborn NS surface due to the perturbation of accreted material during the accretion process. Despite the mild accretion, the clumps formed via accumulation of accreted matter can lead to an abrupt release of redundant thermal energy, manifesting as the outbursts in transient AXPs. The AXPs come into being from LMNBs keep a considerable amount of tidal energy (up to \(10^{48} \text{ ergs}\), Hut & Paczynski 1984), which may contribute to the intense X-ray bursts.

The resultant objects in other three scenarios described in section 5.3, section 4 and section 5 involve both SGRs and AXPs. If the original system experiences re-explosion, the resultant object is an SGR. The accretion onto a denser crust is responsible for a harder X-ray spectrum and the sudden release of energy. The evolution of a "supergiant" TZO is dominated by nuclear energy due to the rp-process in the convective massive envelope, following which comes the neutrino runaway or re-explosion, according to different means by which the nuclear burning is terminated. When the neutrino runaway occurs, the burning of reserved fresh fuel contributes to the accumulation of thermal energy above the NS core, which results in the X-ray variabilities during the subsequent accretion phase of AXPs. Both encounters
of binaries with field stars in GCs (see section 5) and the re-collapse of a newborn NS in a binary or GC (described in section 6) are related to the directly physical star-star collision. Due to the collision being inelastic, the huge striking energy is reserved as thermal energy in the system. Consequently, after blowing off the envelope, the mild accretion from a fallback disk may lead to the occasional release of the reserved thermal energy, even to sudden intense ejection. It is the release of the thermal energy converted by striking energy that results in the X-ray spectrum and variabilities.

8 CONCLUSIONS

Based on the recent challenges to the magnetar model and the facts that AXPs may be the accreting objects, we investigate several scenarios in which SGRs/AXPs are born in normal NS binary systems. We propose that SGRs/AXPs are reborn objects from normal NSs with distinct physical properties. The formation mechanisms are related to the coalescence between a normal NS and the optical companion star and the subsequent evolutions of the coalesced components.

The formation of SGRs rely on re-explosion of the original normal NSs, which can be realized in three scenarios. In "supergiant" TZO, the NS re-explodes as a result of the squeeze of the collapsed massive envelope (with mass \( \geq 10.5 M_\odot \)) triggered by the exhaustion of rp-process seed elements in the "supergiant" TZO structure. On the other hand, the re-explosion of the normal NS can also be triggered by means of direct physical star-star collision. This is expected to occur when the binary encounters a field star in a GC or when a newborn NS with asymmetric kick velocity collides with its companion in the binary or with a field star in a GC. Thanks to the instant collapse of the TZO massive envelope in or physical collision, the re-explosion only involves changes of state in the crust of the original normal NS. Therefore, an SGR is related to an object consisting of a neutron-drip core and a denser crust, accreting from a thin fallback disk. It is the accretion onto the denser crust that is responsible for hard X-ray spectrum in quiescent state and intense variabilities.

We suggest that AXPs are a class of isolated NSs accreting from a massive disk, and that huge thermal energy is reserved in an insulating layer between the NS surface and the massive disk. If an AXP is formed in an LMNB, the tidal oscillation energy converts into thermal energy. If the formation environment involves a less massive system with total mass \( \leq 9 M_\odot \), the accumulated energy mainly consists of gravitational energy with a small part of nuclear energy, while for a massive system with total mass of \( \geq 11.5 M_\odot \), the thermal energy comes from nuclear energy generated via the nuclear-burning above the original NS core. However, if the formation mechanism is related to the inelastic physical star-star collision, the huge striking energy finally converts into thermal energy and deposits. Thanks to the mildly steady release and occasional ejection of the thermal energy, the NS manifests itself as an AXP.

We ascribe the formation of spin clustering to either the brake of slow rotation of the envelope or the frictional drag, according to different formation scenarios. If the original NS coalesce into a massive star, such as in "supergiant" TZO or encounters field stars described in section 5 the massive envelope outside the NS core after coalescence is expected to be a slow rotator. Therefore, the inflows onto the NS core have small angular momentum and spin down the NS core. When the contacted star is a low mass object, the frictional drag due to the relative motion between the NS core and the low-mass envelope contributes to the spin-down of the NS. In this paper we just propose possible mechanisms for the formation of SGRs/AXPs in binaries. Numerical calculations for each scenario will be performed in a series of future works.

ACKNOWLEDGEMENTS

This work was supported by the National Science Council of the Republic of China under grant NSC 99-2112-M-007 -017 -MY3.

REFERENCES

Alpar, M. A. 2001, ApJ, 554, 1245
Alpar, M. A., Pines, D., Anderson, P. W., & Shaham, J. 1984, ApJ, 276, 325
Baykal, A. & Ogelman, H. B., in The Lives of the Neutron Stars, Eds. M. A. Alpar, U. Kiziloglu, J. van Paradijs, Publisher, Kluwer Academic, 1995, p.397
Biehle, G. T. 1991, ApJ, 380, 167
Camilo, F., Kaspi, Y. V., Lyne, A. G., et al. 2000, ApJ, 541, 367
Camilo, F., Ransom, S. M., Halpern, J. P., et al. 2006, Nature, 442, 892
Camilo, F., Ransom, S. M., Halpern, J. P., & Reynolds, J. 2007, ApJL, 666, L93
Cannon, R. C. 1993, MNRAS, 263, 817
Cannon, R. C., Eggleton, P. P., Żytkow, A. N., & Polskiowski, P. 1992, ApJ, 386, 206
Cea, P. 2006, A&A, 450, 199
Chau, W. Y., & Lauterborn, D. 1977, ApJ, 214, 540
Chatterjee, P., & Hernquist, L. 2000, ApJ, 543, 368
Chatterjee, P., Hernquist, L., & Narayan, R. 2000, ApJ, 534, 373
Corbet, R. H. D., Day, C. S. R. 1990, MNRAS, 243, 553
Corbet, R. H. D., Smale, A. P., Ozaki, M., Koyama, K., & Iwasawa, K. 1995, ApJ, 443, 786
Dewey, R. J., & Cordes, J. M. 1987, ApJ, 321, 780
Duncan, R. C., & Thompson, C. 1992, ApJL, 392, L9
Eich, C., Zimmermann, M. E., Thorne, K. S., & Żytkow, A. N. 1989, ApJ, 346
Fabian, A. C., Eggleton, P. P., Pringle, J. E., & Hut, P. 1986, ApJ, 305, 333
Fabian, A. C., Pringle, J. E., & Rees, M. J. 1975, MNRAS, 172, 15P
Faulkner, J. 1971, ApJL, 170, L99
Flannery, B. P., & van den Heuvel, E. P. J. 1975, A&A, 39, 61
Ghosh, P., Angelini, L., & White, N. E. 1997, ApJ, 478, 713
Gotthelf, E. V., Vasishth, G., Boylan-Kolchin, M., & Torii, K. 2000, ApJL, 542, L37
Halpern, J. P., & Gotthelf, E. V. 2010, ApJ, 709, 436

Accreting SGRs/AXPs
