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The youngest X-ray binaries

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Abstract Several X-ray binaries (XRBs) have been identified to be associated with supernova remnants (SNRs). Because of the short lifetimes of SNRs, this leaves them to be the youngest known XRBs. This small group of binaries provides valuable information on the formation of compact stars under the framework of massive binary evolution. In this paper we review the observational characteristics of these youngest XRBs and discuss their possible implications on the initial conditions of compact stars and their interaction with the companion stars.

Key words: accretion, accretion disks — stars: black holes — stars: neutron, evolution

1 INTRODUCTION

X-ray binaries (XRBs) usually consist of an accreting neutron star (NS) or black hole (BH) and an optical companion/donor star (Nagase 1989). According to the masses $M_{\rm C}$ of the companion stars, XRBs can be mainly divided into high-mass X-ray binaries (HMXBs) where $M_{\rm C} \gtrsim 8\,M_\odot$ and low-mass X-ray binaries (LMXBs) where $M_{\rm C} \lesssim 1\,M_\odot$. HMXBs can be further classified into supergiant X-ray binaries (SGXRBs), Wolf-Rayet X-ray binaries (WRXRBs), and Be/X-ray binaries (BeXRBs) (see Reig 2011, for a review). Except for a few close binaries where mass transfer occurs via Roche-lobe overflow (RLOF) of the companion star, in most HMXBs the compact star accretes by capturing the wind material from the massive companion star. In the case of SGXRBs and WRXRBs, the stellar winds are traditionally thought to be radially expanding (probably in the form of clumpy winds), while in BeXRBs the donor stars are fast-rotating B-type stars and the winds are in the form of a circumstellar decretion disk.

Based on the main-sequence (MS) and post-main-sequence (PMS) lifetimes of the companion star, LMXBs and HMXBs have typical ages of $\sim\ 10^9 - 10^{10}$ yr and $\sim 10^6 - 10^7$ yr, respectively. These objects provide unique astrophysical laboratories for studies of stellar evolution, accretion processes and astrophysics of compact stars. HMXBs are especially at the key transitional stage between young massive binaries and double degenerate binaries, which are the important sources of gravitational wave radiation.

Due to the strong interaction between the compact stars and the accreting material, the properties of compact stars such as mass, spin, and magnetic field may have been significantly changed, and thus it is difficult to trace their origins from their current status. Most NSs and BHs are produced by supernovae (SNe) of massive stars. Because supernova remnants (SNRs) are short-lived (with ages $\lesssim 10^5$ yr), studies of XRBs associated with SNRs provide valuable insights into the earliest stages of XRB evolution and accretion history. Fortunately there have been an increasing number of XRBs discovered to be associated with SNRs. In this paper we review the observational characteristics of these youngest XRBs and discuss their possible implications on the formation and evolution of compact stars.

2 X-RAY BINARIES ASSOCIATED WITH SUPERNOVA REMNANTS

Currently there are six XRBs that are (possibly) associated SNRs, including one BH XRB and five NS XRBs. Three of them are in the Milky Way (MW), two in the Small Magellanic Cloud (SMC) and one in the Large Magellanic Cloud (LMC). Table 1 summarizes the observational and derived parameters of these XRBs.

2.1 SS433

SS433 is a well-known Galactic XRB/microquasar with two mildly relativistic (0.26 speed of light) jets (Fabrika 2004, for a review). The binary orbital period is $P_{\rm orb} = 13.1$ d (Crampton et al. 1980; Crampton & Hutchings

Table 1 Properties of the XRBs and Candidates Associated with SNRs[a]

XRB (α, δ) (J2000)	SNR	Compact star	Spectral type of companion star	Age (yr)	Spin period (s)	Orbital period (d)
SS433/3A1909+048 ($19^{\rm h}11^{\rm m}49.60^{\rm s}$, $+04°58'58.0''$)	W50[b]	BH(?)	A7Ib	$\sim 10^4 - 10^5$	-	13.08
Cir X-1/3A1516-569 ($15^{\rm h}20^{\rm m}40.90^{\rm s}$, $-57°10'01.0''$)	G322.1+0.0	NS	B5-A0	~ 3000	-	16.6
SXP 1062 ($01^{\rm h}27^{\rm m}45.95^{\rm s}$, $-73°32'56.3''$)	-	NS	B0-0.5(III)e+	$\sim (2-4)\times 10^4$	1062	$668(\pm 10)$
SXP 1323 ($01^{\rm h}03^{\rm m}37.40^{\rm s}$, $-72°01'34.1''$)	-	NS	B0e III-V	$\sim (2.5-4)\times 10^4$	1323	26.2
MCSNR J0513−6724 ($05^{\rm h}13^{\rm m}42.60^{\rm s}$, $-67°24'12.4''$)	-	NS	B2.5Ib	$\sim 1000-5700$	4.4	$2.2324(\pm 0.0003)$
CXOU J053600.0−673507[c] ($05^{\rm h}36^{\rm m}00.00^{\rm s}$, $-67°35'07.0''$)	SNR 0535−67.5	NS	O5III(f)	$> (5-7)\times 10^4$	-	-

[a] See text for details; [b] the nature of the nebula is not confirmed; [c] the nature of the compact star is not confirmed.

1981) and the jets precess at a period of 164 d (Fabian & Rees 1979; Milgrom 1979). However, the nature of the accreting compact object and its companion star remains highly debated. Based on optical observation of the absorption lines of SS433, Gies et al. (2002) and Hillwig & Gies (2008) suggested that the optical counterpart V1343 Aql has spectral class $\sim$A7Ib, and the latter work estimated the masses of the BH and the companion star to be $M_{\rm X} = 3.3(\pm 0.8)\,M_\odot$ and $M_{\rm C} = 12.3(\pm 3.3)\,M_\odot$, respectively. Similar estimates were obtained by Kubota et al. (2010) with the *Subaru* and *Gemini* observations. However, X-ray eclipse data indicate a smaller mass ratio ~ 0.15, which points to an NS accretor (Brinkmann et al. 1989; Kawai et al. 1989; Kotani et al. 1998). More recent analysis of X-ray eclipses gives a mass ratio $\gtrsim 0.6$, and the mass of the compact object $M_{\rm X} > 5 - 9\,M_\odot$, placing it to be a BH (Cherepashchuk et al. 2018, 2019). The mass loss rate is estimated to be very high, $\sim 10^{-4}\,M_\odot\,{\rm yr}^{-1}$, indicating that the BH is accreting at a supercritical rate.

SS433 is located at the center of W50, a nebula thought to be an SNR at a distance of 5.5 kpc (Margon 1984; Blundell & Bowler 2004)[1]. Hydrodynamical simulations constrain the age of W50 to be $\sim 10^4 - 10^5$ yr (Shklovskii 1980; Zealey et al. 1980; Lockman et al. 2007; Goodall et al. 2011; Panferov 2017), and the duration of the current jet activity to be $\sim 10^3 - 10^4$ yr (King et al. 2000; Bowler 2010). These estimates demonstrate that RLOF of the companion star commenced shortly after the BH was born.

2.2 Cir X-1

Cir X-1 is an unusual XRB whose nature has been a puzzle for many years. Since its discovery in 1971 (Margon 1971), Cir X-1 has shown a vast change in X-ray intensity by two orders of magnitude. The X-ray luminosity can exceed 10^{38} erg s^{-1} (Linares et al. 2010; Heinz et al. 2015). It shows X-ray and radio flare modulations at a 16.6 d period, which is thought to be the binary orbital period (Kaluzienski et al. 1976; Whelan et al. 1977). The presence of type I (i.e., thermonuclear) X-ray bursts (Tennant et al. 1986; Papitto et al. 2010; Linares et al. 2010) confidently identifies the compact star to be an NS with a relatively low magnetic field, but the spin period is not known.

The nature of the companion star remains unclear. Early optical observations identified it as an early-type supergiant (Whelan et al. 1977; Murdin et al. 1980). Later works (Argue & Sullivan 1982; Moneti 1992) showed that the donor star was in fact several magnitudes fainter than that measured by Whelan et al. (1977). It was then suggested to be an MS B star by Haynes (1987), and an MS star with spectral type no earlier than type G by Stewart et al. (1991). More recently, Jonker et al. (2007) detected near-IR Paschen absorption lines in the spectra, and suggested the donor star to be a supergiant star with spectral type B5-A0 and orbital eccentricity $\sim$ 0.45. Johnston et al. (2016) estimated the extinction to Cir X-1 from the strength of the diffuse interstellar bands and the Balmer decrement. They showed that the optical light curve can be modeled as arising from irradiation of the companion star by the central X-ray source, suggesting that the companion star is overluminous and underdense, due to the impact of the SN ejecta.

Based on a deep *Chandra* X-ray observation and radio observations, Heinz et al. (2013) reported the discovery of the natal SNR of Cir X-1. Analysis of the SNR evolution indicates an upper limit of 4600 yr on the age of the remnant, if at a distance of 8 kpc. More recent radio observations determine the distance to Cir X-1 to be $9.4^{+0.8}_{-1.0}$ kpc and the age of the SNR to be $\sim$ 3000 yr.

[1] Begelman et al. (1980) suggested that W50 is a bubble swept in the interstellar medium by the SS433 jets or winds rather an SNR.

This makes Cir X-1 the youngest known XRB. The short timescale for the orbital evolution $P_{\rm orb}/\dot{P}_{\rm orb} \sim 1400 - 3000$ yr also suggests that Cir X-1 be very young (Parkinson et al. 2003; Clarkson et al. 2004).

2.3 SXP 1062

Hénault-Brunet et al. (2012) reported the discovery of a BeXRB SXP 1062 in the Wing of the SMC. The detection of strong X-ray pulsations with a period of 1062 s revealed that the compact star in this system is a slowly rotating pulsar. SXP 1062 shows regular type I outbursts but with a relatively low intrinsic X-ray luminosity $L_{\rm X} \simeq 6 \times 10^{35}$ erg s^{-1}. Its optical counterpart is the Be star 2dFS 3831 with spectral type B0-0.5(III)e+ (Evans et al. 2004; Hénault-Brunet et al. 2012). Regular variations in the optical and X-ray outbursts reveal the orbital period to be $P_{\rm orb} = 668(\pm 10)$ d (Schmidtke et al. 2012; Sturm et al. 2013; González-Galán et al. 2018).

Hénault-Brunet et al. (2012) also detected a shell nebula around the optical counterpart of SXP 1062 in Hα and [O III] images and concluded that it is most likely an SNR. The SNR nature was further confirmed by Haberl et al. (2012) using radio, optical and X-ray images. Adopting a canonical SN explosion energy of $E_{\rm SN} = 10^{51}$ erg, Hénault-Brunet et al. (2012) estimated the current shell kinetic energy to be 3×10^{50} erg, which implies a shell expansion velocity of $350(\pm 100)$ km s^{-1} and an age of $\sim (2 - 4) \times 10^4$ yr. From the temperature derived from X-ray spectral modelling and the size of the SNR, Haberl et al. (2012) estimated the age of the SNR to be $\sim 1.6 \times 10^4$ yr.

2.4 SXP 1323

SXP 1323 is a BeXRB in SMC (Meyssonnier & Azzopardi 1993; Haberl & Sasaki 2000) with a pulse period of 1323 s (Haberl & Pietsch 2005). Follow-up optical spectroscopy observations showed that the optical star is a B0e III-V star (McBride et al. 2008). Schmidtke & Cowley (2006) and Carpano et al. (2017) obtained the binary orbital period to be 26.2 d from the optical and X-ray light curves.

Gvaramadze et al. (2019) showed that SXP 1323 is located at the center of a circular shell which was detected in an Hα image obtained with the Very Large Telescope. This suggests that both objects are physically associated with each other. Follow-up spectroscopy with the Southern African Large Telescope showed that the shell expands with a velocity of about 100 km s^{-1} and that its emission is due to shock excitation. The authors suggested that this shell is an SNR. The ratio of the combined [S II] $\lambda\lambda$6716, 6731 lines against Hα of $0.3 - 0.4$ agrees with the SNR interpretation of the shell. If the SNR is in the adiabatic phase, its age can be estimated to be $(2.5 - 4) \times 10^4$ yr with $E_{\rm SN} = (0.1 - 1) \times 10^{51}$ erg.

2.5 MCSNR J0513−6724

MCSNR J0513−6724 was previously thought to be a candidate SNR in the LMC (Haberl & Pietsch 1999; Bozzetto et al. 2017). In X-rays it displays a shell-like morphology, with a size of $\sim$ 14.5 $\times$ 12.3 pc at the distance of the LMC (50 kpc). Combined radio and X-ray observations showed that emissions in the radio and X-ray wavelengths from the south shell are correlated, and that the brightest and hardest X-ray emission from the south shell is spatially coincident with the brightest radio emission. This confirms its identity as an SNR (Maitra et al. 2019). From the measured SNR radius and shock temperature the authors derived a dynamical age of $\sim 1000 - 5700$ yr.

Moreover, Maitra et al. (2019) discovered a faint X-ray point source at the geometrical center of MCSNR J0513−6724. The $0.2 - 12$ keV luminosity of the source is around 7×10^{33} erg s^{-1}, and its X-ray spectrum is consistent with an absorbed power law with spectral index $\sim$ 1.6. Tentative X-ray pulsations were observed with a periodicity of 4.4 s. The optical counterpart was identified to be BSDL 923, which may be a supergiant with spectral type B2.5Ib. The OGLE I-band light curve of the optical counterpart reveals a period of $2.2324(\pm 0.0003)$ d, indicative of the binary orbital period. All these features point to the fact that the X-ray source is likely an SGHMXB.

2.6 CXOU J053600.0−673507

The SNR 0535−67.5 in the HII region DEM L241 in the LMC was first identified by Mathewson et al. (1985) with combined analysis of optical, radio, and X-ray observations. They showed that DEM L241 has the typical looped filamentary structure of an SNR with a size of $\sim 2'$ in both optical and radio images, and the [SII] to Hα ratio is 0.6. A *Chandra* observation revealed an interior unresolved source, which is probably an accretion-powered binary (Seward et al. 2012). Emission from the remnant interior is thermal and spectral information was used to derive the density and mass of the hot material, from which Seward et al. (2012) obtained an age of $> (5 - 7) \times 10^4$ yr for the SNR. *XMM-Newton* observation by Bamba et al. (2006) showed that the X-ray emission in the soft band reveals an elongated structure with a central pointlike source. From its luminosity and spectrum they argued that the source might be a pulsar wind nebula in DEM L241.

A *Chandra* observation shows that the compact X-ray source CXOU J053600.0−673507 appears point-like and has a luminosity $\sim 2 \times 10^{35}$ erg s^{-1} (Seward et al. 2012). The variability in X-rays excludes an unresolved pulsar wind nebula. It is too bright to be a Cas A-type central compact object whose typical luminosities are $10^{33} - 10^{34}$ erg s^{-1}. Although the X-ray luminosity is compatible with an anomalous X-ray pulsar, the spectrum is harder than that of most anomalous X-ray pulsars. Combining the fact that the optical counterpart HD 269810 is an O5III(f) star, Seward et al. (2012) suggested that CXOU J053600.0−673507 is likely an HMXB comprising an O star and an accreting NS.

However, Cobert et al. (2016) recently discovered luminous gamma-ray emission from CXOU J053600.0−673507 with *Fermi* observation. Periodic modulation in gamma-rays with a 10.3 day period was detected. The radio and X-ray counterparts also exhibit flux modulation on this period. The source properties, including radial velocity measurements of the O5 III(f) counterpart, suggest that the system contains a rapidly rotating NS which may eventually evolve into an XRB. van Soelen et al. (2019) reported on optical spectroscopic observations of the source and obtained an orbital eccentricity $e = 0.40(\pm 0.07)$. The determined mass function, $f = 0.0010(\pm 0.0004)\,M_\odot$, also favors a pulsar wind driven and not accretion driven system.

3 IMPLICATIONS ON THE PROPERTIES OF YOUNG NEUTRON STARS

The discovery of NS XRB-SNR associations provides interesting information about the initial spin period and magnetic field of the NSs, as well as the interaction between young NSs and their companion stars. When the NS captures the envelope material from the companion star by gravity, the motion of the accreting material is also strongly influenced by the NS magnetic field and the particle wind. At the stopping radius the ram pressure of the accreting material is balanced by the magnetic/radiatioin pressure. If the magnetic pressure dominates, the stopping radius is called the magnetospheric radius, which is given by

$$R_{\rm m} = \xi \left(\frac{\mu^2}{\dot{M}\sqrt{2GM}} \right)^{2/7}, \qquad (1)$$

where $\mu = BR^3$, M, and $\dot{M}$ are the magnetic moment, mass, and mass accretion rate of the NS, respectively. Here G is the gravitational constant, B the surface magnetic field, R the radius of the NS, and ξ a dimensionless factor of order unity. A necessary condition for steady accretion onto the NS is that the magnetospheric radius is smaller than the corotation radius where the local Keplerian angular velocity of the accreting material equals the angular velocity Ω of the NS, i.e.,

$$R_{\rm co} \equiv \left(\frac{GM}{\Omega^2} \right)^{1/3}. \qquad (2)$$

Accordingly the spin period P of the NS should be longer than the equilibrium period

$$P_{\rm eq} = 2^{11/14} \pi \xi^{3/2} \mu^{6/7} \dot{M}^{-3/7} (GM)^{-5/7}, \qquad (3)$$

or

$$B \leq 8.5 \times 10^{10} (\xi_{0.5}^{-9/7} M_{1.4}^{1/3} R_6^{-5/2}) P^{7/6} L_{35}^{1/2}\ {\rm G}, \qquad (4)$$

where $\xi_{0.5} = \xi/0.5$, $M_{1.4} = M/1.4\,M_\odot$, $R_6 = R/10^6$ cm, and $L_{35} = L_{\rm X}/10^{35}$ erg s^{-1}. For MCSNR J0513−6724, assuming a correction factor of two for the bolometric luminosity and adopting the spin period of 4.4 s, one can derive the upper limit of the NS surface magnetic field strength to be $(2-5) \times 10^{11}$ G (see also Maitra et al. 2019). In the case of Cir X-1, the presence of type I X-ray bursts (Tennant et al. 1986; Linares et al. 2010) indicates that the NS possesses a relatively low magnetic field strength ($< 10^{12}$ G) (Joss & Li 1980; Fujimoto et al. 1981). At the observed luminosity of Cir X-1, the emission radius of the blackbody is small enough to be associated with the accretion hot spot as the X-ray emitting region, which also points to a field strength below 10^{12} G (Schulz et al. 2020). Thus these two objects could belong to the group of so-called "anti-magnetars" (young NSs born with a weak dipole field), originally discovered in the compact central objects (CCOs) in SNRs, like 1E 1207.4−5209 in G296.5+10.0 (Zavlin et al. 2000; Gotthelf & Halpern 2007), CXOU J185238.6+004020 in Kes 79 (Haberl 2007), and RX J0822−4300 in Puppis A (Gotthelf & Halpern 2009). An interesting scenario for these objects suggests that rapid fallback accretion after the SN explosion (Chevalier 1989) may bury the magnetic field of the NS and decrease its surface strengths (Bernal et al. 2013; Torres-Forné et al. 2016). The buried field then gradually reemerges through Hall drift and Ohmic dissipation when accretion stops (Geppert et al. 1999; Ho 2011; Pons et al. 2013; Viganò et al. 2013; Gourgouliatos & Cumming 2015). The typical timescale of the reemergence is $\gtrsim 10^3$ yr (Ho 2011; Gourgouliatos & Cumming 2015), depending on the burial depth.

A newborn NS is believed to rapidly rotating. The relativistic winds from the rotation-powered NS can prevent the companion's matter from penetrating the light cylinderical radius or the Bondi gravitational radius, so the NS usually first appears as a radio pulsar and spins down by magnetic dipole radiation. Once the plasma enters the light cylindrical radius, the pulsar mechanism switches off and the incoming matter forms a quasi-static atmosphere surrounding the NS (Davies et al. 1979). Since $R_{\rm m} > R_{\rm co}$ in this situation, the infalling material is stopped at the magnetosphere by the centrifugal barrier, which prevents material from accreting onto the NS. The ejected material carries away the angular momentum of the NS and decelerate its spin by the propeller mechanism (Illarionov & Sunyaev 1975). The system finally switches on as an accreting XRB when the NS spin period has reached $P_{\rm eq}$, where $R_{\rm m} = R_{\rm co}$. Thus, to reach the current spin period the NS should have already experienced the ejector and propeller phases. Most X-ray pulsars in HMXBs have a spin period of tens or hundreds of seconds with an age in excess of 10^6 yr. In contrast, the spin periods of SXP 1062 and SXP 1323 are longer ($\sim 10^3$ s), but their ages are much shorter ($\sim 10^4$ yr). So it is interesting to ask how the NSs can spin down to such a long period within such a short time.

Haberl et al. (2012) argued that, if an NS has a normal magnetic field ($B \sim 10^{12} - 10^{13}$ G), it is difficult to spin-down to a period $\sim 1000\,$s within a few 10^4 years. Assuming that SXP 1062 has spun down with a constant rate $\dot{P} = 100$ s yr^{-1} as observed over its whole lifetime, they derived the lower limit of the initial spin period of the NS to be 0.5 s. Assuming that SXP 1062 is spinning at the equilibrium period, Popov & Turolla (2012) derived the current NS magnetic field to be $\lesssim 10^{13}$ G. To reconcile the long spin period and short age of SXP 1062, they suggested that the NS magnetic field must be in excess of 10^{14} G in the past and then decayed to its present, normal value. Thus SXP 1062 may be a unique example of evolved magnetars in HMXBs. Fu & Li (2012) explored the possible evolutionary tracks of SXP 1062, taking account of various initial parameters and spin-down mechanisms of the NS. They showed that the current magnetic field of the NS may be $\gtrsim 10^{14}$ G. As such, SXP 1062 would be an accreting magnetar. González-Galán et al. (2018) estimated the magnetic field for SXP 1062 adopting the quasi-spherical accretion model of Shakura et al. (2012), and found no need for an extremely high magnetic field at present day for SXP 1062. However, it is noted that in the model of Shakura et al. (2012) the estimation of the NS $B-$field is sensitively dependent on a few parameters whose magnitudes are uncertain. Additionally, the Shakura et al. (2012) model was constructed for NSs accreting from spherically expanding winds in HMXBs, while in the case of SXP 1062 the winds from the Be star is in the form of a decretion disk, and it is unknown whether the model applies in that case. For example, the timing analysis by Serim et al. (2017) shows that SXP 1062 has a long-term secular steady spin-down that could be a result of a steady disk accretion. Using the standard accretion theory, Serim et al. (2017) obtained a magnetar-like surface magnetic field estimation that is consistent with the estimations by Fu & Li (2012)

If SXP 1062 is or has been a magnetar, so is SXP 1323. Thus, we see the diversity of youngest NSs in the small sample of youngest XRBs[2]. Considering the fact that young isolated NSs can manifest themselves as magnetars, high-B pulsars, and CCOs, some of NS sub-populations could be connected with similar evolutionary paths but with different initial field configurations in terms of the magnetothermal evolution model (Kaspi 2010; Popov et al. 2010; Pons et al. 2013; Viganò et al. 2013; Gullón et al. 2015). While the magnetothermal evolutionary model is mainly applicable for NSs with high magnetic fields ($\gtrsim 10^{13}$ G), to unify NSs with both low and high surface fields one may need to invoke the field burial and reemergence model (Viganò & Pons 2012; Heinz et al. 2015; Popov et al. 2015; Rogers & Safi-Harb 2016; Liu & Li 2019).

4 THE EVOLUTIONARY PICTURES FOR SS433 AND CIR X-1

The mass transfer in XRBs occurs through two ways: capture of the wind from the companion star and RLOF. In the former case, to ensure efficient mass accretion onto the compact star requires both high wind mass loss rate and short orbital separation. This is why most HMXBs possess a supergiant donor star in close orbit or a Be star in long and eccentric orbit. While MCSNR J0513−6724, SXP 1062, and SXP 1323 readily fit the BeXRB picture, the luminous X-ray emission and jet activity in SS433 and Cir X-1 clearly indicate rapid mass transfer caused by RLOF. It is then interesting to ask how the companion star can fill its RL shortly after the SN for the latter systems.

Although there have been extensive investigations on the formation and evolution of various types of XRBs, to our knowledge, Han & Li (2020) and Xing (2020) are the only theoretical works that investigate the formation of RLOF XRBs within the SNR's lifetime, which focus on SS433 and Cir X-1, respectively.

Assuming that the compact object in SS433 is a BH, Han & Li (2020) employed a binary population synthesis (BPS) method[3] to study the formation of SS433. After evolving a large number of primordial binaries, they searched the BH binaries in the BPS results whose XRB

[2] Assuming that the current spin period of MCSNR J0513−6724 is around the equilibrium period, Maitra et al. (2019) estimated its magnetic field to be less than 5×10^{11} G. However, Ho et al. (2020) argued that the NS is unlikely to be an accretor because of the long duration of the ejector and propeller phases. They instead suggested that the NS is likely to be in the propeller phase and has a magnetic field $B >$ a few$\times 10^{13}$ G.

[3] see Han et al. (2020) in this special issue (Wang & Ip 2020) for a recent review of BPS.

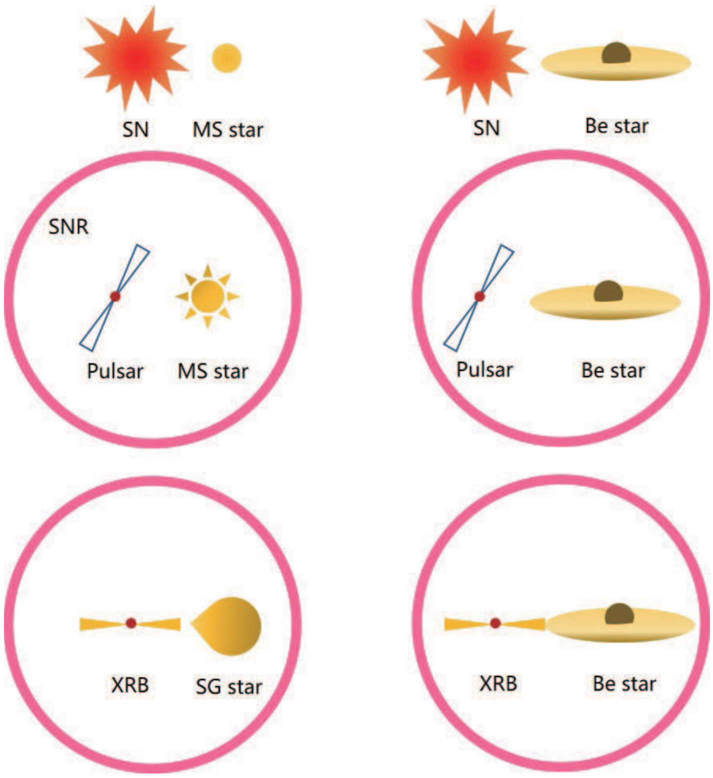

Fig. 1 Demonstration for the early-stage evolution of a newborn NS with a massive companion star. In the left and right panels the companion star is an MS star with radially expanding wind and disklike wind, respectively.

phase starts within 10^5 yr since the birth of the BH. Other selection criteria include: (1) the mean mass transfer rate $> 10^{-8}\, M_\odot$ yr^{-1}, (2) the companion mass is initially less than $50\, M_\odot$, and (3) the orbital period at the beginning of RLOF is less than 1 yr. It is found that the properties of the selected binaries span a wide range and can be divided into three groups according to the evolutionary stage of the companion star: (1) BH binaries with an MS companion, (2) BH binaries with a Hertzsprung gap (HG) companion, and (3) BH binaries with a core helium burning (CHeB) star or helium main-sequence (HeMS) star companion. The overall birthrate of the BH binaries is a few times 10^{-6} yr^{-1}. If one sets more stringent constraints for SS433 such as the time the companion spent to fill its RL after the BHs birth is less than 10^4 yr, the orbital period is shorter than 20 days at the end of the RLOF, and the duration of the RLOF phase is longer than 10^3 yr, then only BH/HG binaries are left, and the birthrate decreases to $\sim 10^{-7}$ yr^{-1}. Detailed mass transfer calculation shows that at the moment of SN, both the companion mass and the orbital period were larger than the current values. The companion star evolved rapidly within the lifetime of the SNR and transferred mass to the BH, which causes significant mass loss and orbital shrink. Considering the fact that the birthrate of BH binaries in the Galaxy is a few $10^{-5} - 10^{-4}$ yr^{-1} (Shao & Li 2018) and there is only one BH XRB (i.e., Cygnus X-1) discovered in the Galaxy, the very low birthrate of SS433 suggests that either we are extremely lucky to observe such a rare object or the actual age of SS433 is much longer than 10^5 yr.

The case of Cir X-1 is probably more complicated because the spectral type of the optical counterpart is highly uncertain. Xing (2020) also investigated its formation with a BPS method, taking into account asymmetric SN kick imparted on the newborn NS. Due to mass loss and the SN kick, the binary orbits are likely to be eccentric after the SN. By selecting binaries where RLOF initiates within 10^5 yr at periastron after the SN, he found that the birthrate of NS XRBs with an MS donor star is $\sim (5-10)\times 10^{-6}$ yr^{-1}. Thus, if taking the upper limit of the SNR ages to be 10^5 yr, there could be at most one such source in the MW. The birthrate for a supergiant donor is smaller, $\sim (1-4)\times 10^{-6}$ yr^{-1}, because of the much shorter lifetime of supergiants. If one considers the donor star to be a Be star and assumes that RLOF takes place at periastron when the Be star disk is larger than its RL, then the birthrate of these binaries can be obtained to be $\sim (5-10)\times 10^{-5}$ yr^{-1}. It clearly demonstrates that the BeXRB model is most likely to account for the characteristics of Cir X-1 (see also Schulz et al. 2020).

Figure 1 illustrates the possible evolutionary tracks for an SGXRB (left) and a BeXRB (right) that starts emitting

X-rays within the lifetime of the SNR. Here we assume that the compact star is an NS. Before it accretes from the companion star and becomes an X-ray source, the NS experiences a phase of radio pulsar because the stellar wind was originally relatively weak and/or the NS was initially rapidly rotating.

5 SUMMARY

BHs and NSs are born in core-collapse of massive stars, and are naturally expected to be found inside or nearby SNRs. While there are more than 120 isolated pulsars thought to be associated with Galactic SNRs (Ferrand & Safi-Harb 2012)[4], we have only five or six cases for accreting compact binaries. Their very low birthrate implies that the total number in the MW and MCs is limited. Nevertheless, this small group of youngest XRBs can provide valuable clues to the initial condition of newborn compact stars, their interaction with environments, and the formation channels of compact star binaries. However, there are quite a few critical issues needed to be addressed, such as the mass of the compact star and the nature of surrounding bubble for SS433, the evolutionary state of the companion star of Cir X-1, the magnetic field strengths of SXP 1062 and SXP 1323, etc. More careful multi-wavelength observations are needed to set stringent constraints on the stellar and binary parameters and differentiate between models for their formation and evolution.

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