Evolving Neutron Star Low-Mass X-ray Binaries to Ulta-compact X-ray Binaries

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1   Introduction

Mass transfer in neutron star low-mass X-ray binaries (NS LMXBs) is either driven by loss of orbital angular momentum or nuclear evolution of the donor star, causing the orbit to the shrink or expand respectively. The "bifurcation period" $P_{\rm bif}$, the initial binary orbital period which separates the formation of converging systems from the diverging systems (Tutukov et al. 1985) was found to be in the range $\sim 0.4 - 0.7$ day for LMXBs, and strongly dependent on magnetic braking (MB) (Pylyser & Savonije 1988). For sufficiently small initial orbital periods, the evolution may lead to the formation of of ultra-compact X-ray binaries (UCXBs) with orbital periods ($P < 50$ min), in which the donor is a white dwarf or a compact core of an evolved giant star (Nelson et al. 1986; Tutukov et al. 1987; Pylyser & Savonije 1988; Podsiadlowski et al. 2002; van der Sluys et al. 2005).

In this work we present the results on the evolution of NS LMXBs and the formation of UCXBs (Ma & Li 2009 for details). We consider the following processes related to mass and angular momentum loss mechanisms in LMXB evolution. (1) The standard MB law (Verbunt & Zwaan 1981; Rappaport et al. 1983) was shown to be contradicted with the observation of young stars in open clusters, and a modified version was proposed (Sills et al. 2000; Andronov et al. 2003). (2) There is strong evidence that during LMXB evolution the mass transfer is highly non-conservative. Possible ways of mass loss include "evaporation" of the donor (Ruderman et al. 1989) or "radio-ejection" of the transferred material (Burderi et al. 2001, 2002; D'Antona et al. 2006) due to the pulsar radiation/wind impinging on. In the latter case, the matter is lost from the system at the inner Lagrangian (L_1) point, carrying away angular momentum and altering the period evolution. Additionally, a small fraction of the mass lost from the donor may form a circum-binary (CB) disk around the binary rather accretes onto the NS (van den Heuvel 1994).

2 Evolution code and binary mode

2.1 The stellar evolution code

We use an updated version of the stellar evolution code originally developed by (Eggleton 1971, 1972) to calculate the evolutions of binaries consisting of an NS (of mass M_1) and an MS secondary (of mass M_2). For the secondary star we assume a solar chemical composition ($X = 0.70$, $Y = 0.28$, and $Z = 0.02$). We assume that the spin of the secondary star and the binary orbital revolution are always synchronized. Assuming rigid body rotation of the secondary star and neglecting the spin angular momentum of the neutron star, the total angular momentum J of the binary system can be expressed as

$$
\begin{aligned}
J &= I_2\omega + J_{\mathrm{orb}} \\
&= I_2\omega + G^{2/3}M_1M_2(M_1 + M_2)^{-1/3}\omega^{-1/3}
\end{aligned}
\tag{1}
$$

where I_2 is the moment of inertia of the secondary star, G the gravitational constant, and ω the angular velocity of the binary.

We consider three kinds of mechanisms of angular momentum loss. The first is the angular momentum loss due to gravitational radiation

$$
\frac{\mathrm{d}J_{\mathrm{GR}}}{\mathrm{d}t} = -\frac{32}{5}\frac{G^{7/2}}{c^5}\frac{M_1^2 M_2^2(M_1 + M_2)^{1/2}}{a^{7/2}},
\tag{2}
$$

where a is the orbital separation and c is the speed of light.

The second angular momentum loss mechanism is for non-conservative mass transfer. We assume that a small fraction $\delta(\ll 1)$ of the mass lost from the donor feeds into the CB disk rather leaves the binary, which yields a mass injection rate of the CB disk as $\dot{M}_{\mathrm{CB}} = -\delta\dot{M}_2$. Tidal torques are then exerted on the binary by the CB disk via gravitational interaction, thus extracting the angular momentum from the binary system. The angular momentum loss rate via the CB disk is estimated to be (Taam & Spruit 2001)

$$
\frac{\mathrm{d}J}{\mathrm{d}t}|_{\mathrm{CB}} = -\gamma\left(\frac{2\pi a^2}{P}\right)\dot{M}_{\mathrm{CB}}\left(\frac{t}{t_{\mathrm{vi}}}\right)^{1/3},
\tag{3}
$$

where $\gamma^2 = r_{\mathrm{i}}/a = 1.7$ (r_{i} is the inner radius of the CB disk), t is the time since mass transfer begins. In the standard α-viscosity disk (Shakura & Sunyaev 1973), the viscous timescale t_{vi} at the inner edge r_{i} of the CB disk is given by $t_{\mathrm{vi}} = 2\gamma^3 P/3\pi\alpha\beta^2$, where α is the viscosity parameter (we set $\alpha = 0.01$ in the following calculations), $\beta = H_{\mathrm{i}}/r_{\mathrm{i}} \sim 0.03$ (Belle et al. 2004), and H_{i} is the scale height of the disk. We also assume that the NS accretion rate is limited to the Eddington accretion rate, and that when the mass transfer rate is less than $\dot{M}_{\mathrm{Edd}}$, half of the mass is accreted by

the NS, i.e., $\dot{M}_1 = \min(\dot{M}_{\rm Edd}, -\dot{M}_2/2)$. The excess mass is lost in the vicinity of the NS through isotropic winds, carrying away the specific angular momentum of the NS, i.e.

$$\frac{{\rm d}J}{{\rm d}t}\Big|_{\rm ML} \simeq \begin{cases} \frac{1}{2}\dot{M}_2 a_1^2 \omega, & |\dot{M}_2| < 2\dot{M}_{\rm Edd} \\ (\dot{M}_2 + \dot{M}_{\rm Edd})a_1^2 \omega, & |\dot{M}_2| \geq 2\dot{M}_{\rm Edd} \end{cases} \tag{4}$$

where $a_1 = aM_2/(M_1 + M_2)$ is the orbital radius of the NS, and ω is the orbital angular velocity of the binary.

The third angular momentum loss mechanism is MB. We use the saturated magnetic braking law suggested in Sills et al. (2000),

$$\frac{{\rm d}J}{{\rm d}t}\Big|_{\rm MB} = \begin{cases} -K\omega^3 \left(\frac{R_2}{R_\odot}\right)^{1/2} \left(\frac{M_2}{M_\odot}\right)^{-1/2}, & \omega \leq \omega_{\rm cr} \\ -K\omega_{\rm cr}^2 \omega \left(\frac{R_2}{R_\odot}\right)^{1/2} \left(\frac{M_2}{M_\odot}\right)^{-1/2}, & \omega > \omega_{\rm cr} \end{cases} \tag{5}$$

where $K = 2.7 \times 10^{47}$ gcm^{2}s (Andronov et al. 2003), $\omega_{\rm cr}$ is the critical angular velocity at which the angular momentum loss rate reaches a saturated state, and can be estimated as ((Krishnamurthi et al. 1997),

$$\omega_{\rm cr}(t) = \omega_{\rm cr,\odot}\frac{\tau_{\rm t_0,\odot}}{\tau_{\rm t}}, \tag{6}$$

where $\omega_{\rm cr,\odot} = 2.9 \times 10^{-5}$ Hz, $\tau_{\rm t_0,\odot}$ is the global turnover timescale for the convective envelope of the Sun at its current age, $\tau_{\rm t}$ for the secondary at age t, solved by integrating the inverse local convective velocity over the entire surface convective envelope (Kim & Demarque 1996).

3   Results

The formation and evolutionary paths of UCXBs depend on the adopted values of δ. To illustrate the effects of δ on the binary evolution, in Figs. 1 and 2, we plot the evolution of the donor mass and period as a function of age respectively, for a binary system with $M_{2,\rm i} = 1.1M_\odot$, $P_{\rm i} = 1.04$ d and different values of δ. A larger value of δ leads to shorter formation time, as seen from Fig. 2; if δ is too small, the binary will not be able to reach the 50 min period within 13.7 Gyr due to inefficient angular momentum loss. When $\delta < 0.0055$, the orbital period first decreases with mass transfer until the donor star loses its outer envelope and shrinks rapidly at $P \sim 0.1 - 0.2$ d. This causes a cessation of mass transfer. In the subsequent evolution the orbital period may decrease down to the ultra-short regime under the effect of GR, until the secondary star fills its RL again, and the binary appears as a UCXB. When $\delta \geq 0.0055$ the binary evolves directly into the ultra-short regime with decreasing orbital period.
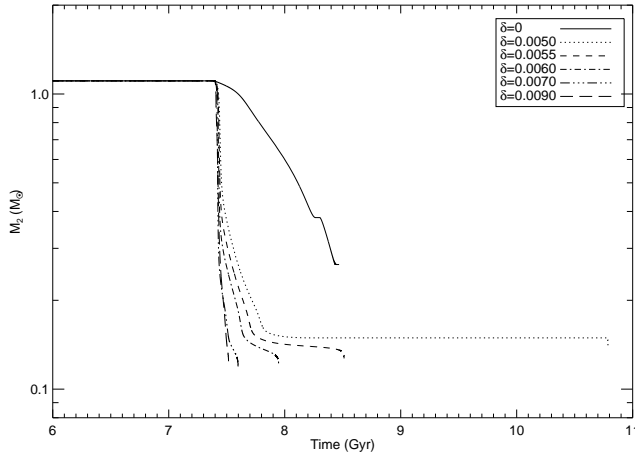
Figure 1: Evolution of the donor mass for different values of the CB disk parameter δ.

We need to mention that the distribution of δ depends on the value of the viscous parameter α. From Eqs. (3) one can see that the CB disk-induced angular momentum loss rate is proportional to $\alpha^{1/3}\delta$. So if keeping $\alpha^{1/3}\delta$ constant, the binary evolution will be exactly the same.

4   Comparison with observations

There are currently 10 UCXBs with known periods, 5 of which are persistent sources and 5 are transients. To compare observations with our CB disk-assisted binary model, we plot the $\dot{M}_1(= -\dot{M}_2/2)$ vs. P_{orb} relations in Fig. ?? for binary systems with $M_2 = 1.1 M_\odot$, $P_{\mathrm{i}} = 1.04$ d and $\delta = 0.005 - 0.009$. We also indicate in Fig. 3 whether the accretion disks in the LMXBs are thermally and viscously stable, according to the stability criterion for a mixed-composition ($X = 0.1$, $Y = 0.9$) disk from Lasota et al. (2008) We use the symbols $\times$, $*$, and $+$ on the evolutionary tracks to denote where the hydrogen composition X of the donor becomes 0.3, 0.2, and 0.1, respectively. The positions of UCXBs are marked in these two figures with circles and triangles for persistent and transient sources, respectively. Besides them, we also include 18 NS LMXBs with known P and $\dot{M}_1$ (data are taken from Liu et al. 2007; Watts et al. 2008; Heinke et al. 2009).

A comparison between our CB disk-assisted binary models and the observations of (compact) NS LMXBs suggesting that it is possible to form UCXBs from normal LMXBs. We note that three of the UCXBs are in globular clusters, indicating low metallicities in these systems. However, from our calculations we find that change
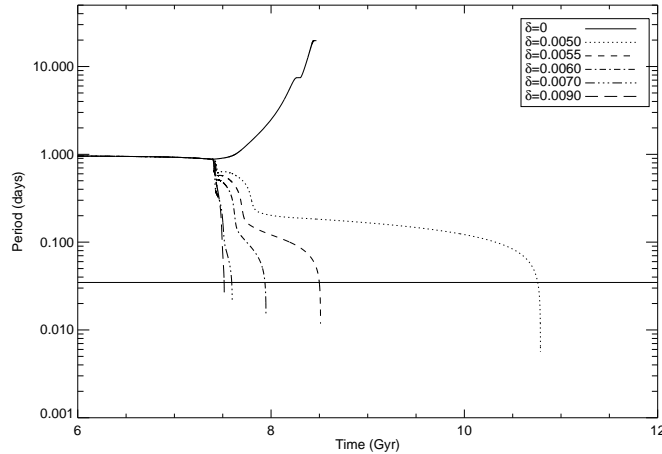
Figure 2: Evolution of the orbital period for different values of the CB disk parameter δ.

of metallicities does not significantly affect the binary evolution when the CB disk is involved.

5 Conclusion

During mass transfer in LMXBs, a CB disk may be formed as a result of mass outflow from the accretion disk, and has been invoked as an efficient process for the removal of orbital angular momentum (Taam & Spruit 2001). We propose a scenario for the formation of UCXBs from L/IMXBs with the aid of a CB disk in this work. The suitable binary parameter space ($M_{2,i}$ and P_i) with reasonable choice of the CB disk parameter δ for the formation of UCXBs within 13.7 Gyr is found to be significantly larger than in previous "magnetic capture" model (van der Sluys et al. 2005). This difference is caused by the fact that the bifurcation period is considerably increased if the CB disk is included.

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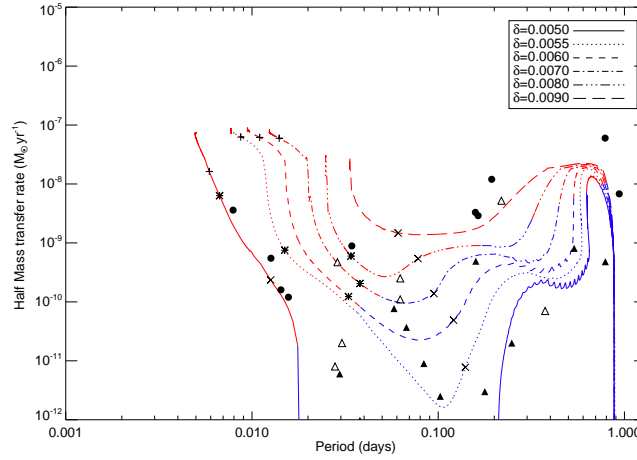[1] Andronov, N., Pinsonneault, M., & Sills, A. 2003, ApJ, 582, 358

Figure 3: Evolution of the mass accretion rate vs. orbital period for different values of the CB disk parameter δ.

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