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Evolution of wind-fed high mass X-ray binaries

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Abstract. The evolution tracks of wind-fed high mass X-ray binaries (HMXBs) involving neutron stars (NSs) are considered. We have constructed a binary evolution code which solves the evolution of NS magnetic field and spin, at the same time as donor evolution and consequent binary evolution. Through the computations, we identify the spin-up / spin-down regimes and obtain the entire evolutions of the orbital periods of wind-fed HMXBs. We found that these periods are relatively conserved their initial periods. On the other hand, we could not reproduce the most slowly rotating NSs in wind-fed systems, which show longer spin-periods than 1 000s. It means that there are some missing spin-down mechanisms rather than that due to NS magnetic field. Probably, subsonic shell formation could play an important role in the spin evolution of NSs in wind-fed HMXBs.

Key words. accretion, accretion disks – stars: neutron – X-rays: binaries

1. Introduction

High mass X-ray binaries (HMXBs) harboring neutron stars (NSs) can be classified into two classes based on their mass-donor type; Supergiant (SG) type and Be type (Corbet 1986; Bildsten et al. 1997). It is well known that the spin period of Be type HMXBs show strong correlation to the orbital period of the binary systems, while SG type systems show no clear correlation. Furthermore, some NSs in SG HMXBs have quite slow spin period, up to 10ks. It is often considered that the rotation rate of the NS is strongly related to its magnetic field. Assuming the spin equilibrium condition, the slow spin period could be realized when NS magnetic field is enough strong. From the observations of cyclotron lines, however, the magnetic field of NSs in SG HMXBs are much less than 10^{14}G, and typically they are all 10^{12}G level (Taani et al. 2018). Hence, the origin of the extremely slow rotations of NSs in some SG HMXBs becomes a puzzle to be solved.

In this study, we try to solve the entire evolutions of the NS spin in wind-fed SG HMXBs. In this purpose, we compute the evolution of the binary system containing an accreting NS and a massive mass donor. From the evolution history of the HMXB systems, we consider the condition to reproduce NSs rotating extremely slow rates. As the preliminary result, we show that the extremely slow NS rotations in SG HMXBs cannot be caused by the dipole radiation and propeller spin down even when we consider strong magnetic field of NSs initially. To explain the slow rotations of NSs, it is required to include some missing spin-down physics, most probably subsonic shell formation.

2. Binary evolution model

We compute a time evolution of binary parameters of the HMXB, besides the stellar evolution of the massive donor. In this binary evolution computation, we consider the mass and angular momentum transfer rate from the donor wind. As the numerical code for binary evolution model, we use a modified version of well-tested BSE code (Hurley et al. 2002). As a mass transfer from the massive donor to the accreting NS via stellar wind, we implement the modified Hoyle-Littleton model (Wang 1981; Karino et al. 2019). Considering CAK wind acceleration, the standard β formarism and the mass loss model for massive stars is used (Vink et al. 2001). For the spin evolution of NS, we consider accretion spin up, at the same time with the spin down due to propeller effect and dipole radiation energy loss (Ghosh 2007). The evolution of NS magnetic field is followed under the assumption of Hall / Ohmic diffusion and the accretion induced field decay (Aguilera et al. 2008; Popov & Tyrolla 2012; Zhang & Kojima 2006). Since the spin evolution proceed in much shorter time comparing with the nuclear time of donor, we impose shorter time-stepping than original BSE code to cover spin evolutions.

An example of binary evolution is shown in Fig. 1. In this figure, an evolution of a typical wind-fed HMXB ($P_s - P_o$ diagram) is shown in Corbet diagram. The modeled binary system initially has a set of parameters shown by *model A* in Table 1; namely, it has $P_s = 0.01$s and $P_o = 10$d, respectively.

Along the evolution track, first, the spin period increases rapidly because of propeller spin-down mechanism. After the end of propeller phase, it spins down continuously due to dipole radiation back-reaction. Then, the accretion spin-up roughly balances to the spin-down due to dipole radiation. The system spends a half of life-time in relatively slowly rotating, low luminosity phase, under this quasi-equilibrium condition. Later we will see, however, that the duration of this quasi-equilibrium phase strongly depends on the set of initial parameters. Since the donor star continuously decreases its mass via wind mass-loss, the orbit of the binary system extends gradually. During this phase, the initially strong magnetic field decays to the normal NS level, $B \sim 10^{12}$G. At the same time, because of the expansion of the donor, the mass accretion rate and consequent spin-up effect becomes dominant. When the donor expand to the nearly Roche-lobe size, then, the tidal effect becomes so strong and the orbit changes drastically. Finally, when the donor fills its Roche-lobe, the wind-fed phase ends and binary proceeds rapid mass-transfer due to RLOF.

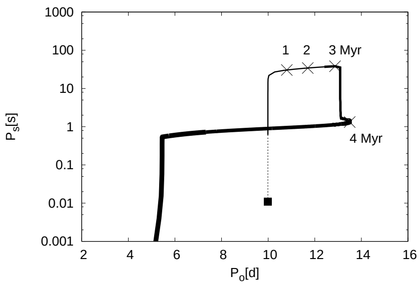

Fig. 1. Example of binary evolution in Corbet diagram (model A).

Table 1. Initial model parameters

Star	model A	model B	model C
M_d	$30M_\odot$	$20M_\odot$	
M_{NS}	$1.4M_\odot$		
P_o	10d		5d
P_s	0.01s		
B_{NS}	10×10^{14}G		
e	0.5		

3. Discussion and conclusion

With newly constructed binary evolution code, the evolution tracks of HMXBs involving NSs have been considered, including the evolution of NS magnetic field and spin. With this code, we also could identify the lifelong variations of X-ray luminosities of HMXBs. Here, we show two more example of evolution tracks of

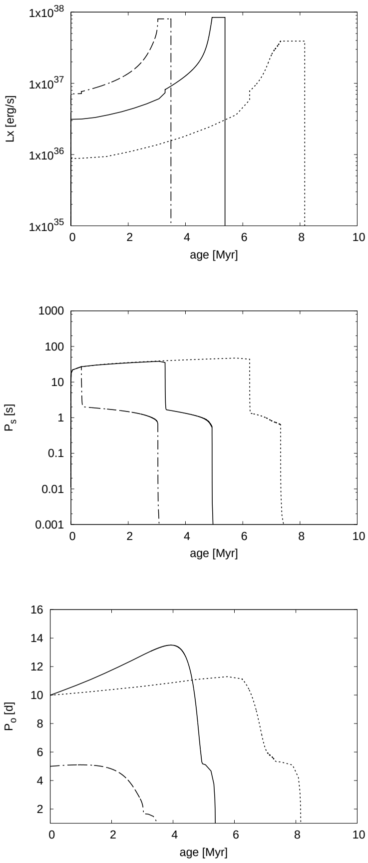

Fig. 2. Example of binary parameters: X-ray luminosity (upper panel), spin period of NS (middle) and orbital period (lower). Three models are shown: model A with solid line, model B with dashed line, and model C with dashed-dotted line, respectively.

SG HMXBs. The used initial parameters are shown in Table 1: the model B is a system with smaller donor mass, while model C is a system with shorter orbital period. The comparison of the main binary parameters (X-ray luminosity, spin period of NS, and orbital period) are shown in Fig. 2.

The important feature is that, in all cases the spin period could not achieve 100s. In our computation, although the NS has strong field ($B \sim 10^{14}$G) initially, the effect of accretion spin-up is so strong and inhibit further spin-down. Since, even the strongest magnetic field model cannot reproduce slowly rotating NS, some missing spin-down mechanism should be considered. Most probably, NS field interaction with settling subsonic shell could be important. Though we have not included this effect, it probably causes strong spin down effect, and contributes the NS spin evolution crucially (Shakura et al. 2012).

Another interesting result which is worth to note is that the initial value of the orbital period is relatively conserved during main evolutionary phase, especially in tight systems. The initial orbital period of a binary including a NS, is strongly related with the natal kick at the birth of NS. From the observed (conserved) orbital periods of systems, if we have large number of SG HMXBs samples, we may derive information of physics of SN kick. In future, such a binary evolution computations involving the NS intrinsic parameters may also explain the burst behavior of SFXT, and may contribute to solve the questions of birth rate of pulsating ULXs, which concerning with critically accreting NSs.

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