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Population synthesis of high mass X-ray binaries *

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Abstract By simulating the evolution of spin periods of magnetized neutron stars which interact with their environment in binary systems, we investigate the Galactic population of high mass X-ray binaries (HMXBs). The number of HMXBs in the Galaxy is between 190 and 240, and their birthrate is from $5.9 \times 10^{-5}\,\mathrm{yr}^{-1}$ to $6.3 \times 10^{-5}\,\mathrm{yr}^{-1}$. Comparing the Corbet diagram (the positions of the spin periods vs. the orbital periods of HMXBs) in our model with the associated observations, we find that the stellar wind structure and the process of matter transfer are very important for understanding HMXBs.

Key words: stars: evolution — X-rays: binaries — Galaxy: stellar content

1 INTRODUCTION

High mass X-ray binaries (HMXBs) are X-ray sources composed of an early-type (O- or B-type) massive star ($M \geq 10\,M_\odot$) and an accreting compact object (neutron star (NS) or black hole). The vast majority of HMXBs contain magnetized NSs, and this work focuses on HMXBs with NSs. The X-ray emission in these sources is due to matter being accreted from an early-type star which is losing mass. HMXBs are interesting objects because they allow us to study a number of fundamental physical questions ranging from estimating their masses to the equation of state of NSs (van der Meer et al. 2007), as well as the stellar structure of the accretion disk in high magnetic fields, and so on. In addition, they can provide information on star formation rates in galaxies because of their age (Grimm et al. 2003).

Many works on the theoretical evolution of HMXBs have been published (e.g. van den Heuvel & Heise 1972; Bhattacharya & van den Heuvel 1991; Iben et al. 1995). Terman et al. (1998) investigated the population of HMXBs via a statistical Monte Carlo approach. After about a decade, many physical parameters of HMXBs have been discovered, especially the spin periods (P_s) of NSs and their orbital periods (P_orb). In a recent list of known HMXBs provided by Liu et al. (2006), there are about 114 HMXBs, in which P_s values of NSs in 66 HMXBs and P_orb values of 50 HMXBs are observed. There are 38 HMXBs in which both P_s and P_orb are observed. According to the theoretical model of the interaction of a rotating magnetized NS with surrounding matter, P_s is a very important physical parameter (e.g. Pringle & Rees 1972; Lovelace et al. 1999).

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Recently, Zhang et al. (2004) and Dai et al. (2006) have calculated the detailed spin evolution of a wind-fed neutron star in a HMXB system. In this work, we focus on the formation of HMXBs and their evolution (including the evolution of $P_{\rm s}$), and investigate the population of HMXBs in the Galaxy. In Section 2 we present our assumptions and describe some details of the modeling algorithm. In Section 3 the properties of the model population of HMXBs are described. Conclusions are presented in Section 4.

2 MODEL

For the simulation of binary evolution, we use the rapid binary star evolution code (BSE) which originated from Hurley et al. (2002) and was updated by Kiel & Hurley (2006). If any input parameter is not specially mentioned, it is taken as a default value from Hurley et al. (2002) and Kiel & Hurley (2006).

2.1 Formation of Neutron Stars

NSs can originate from core-collapse supernovae, electron capture supernovae or accretion-induced collapses. In this work, we focus on the first channel, that is, all NSs in HMXBs which form via core-collapse supernovae. In forthcoming work, other channels will be studied. Stars with main-sequence mass $M/M_\odot \geq 11$ experience core-collapse supernovae (Podsiadlowski et al. 2004). A nascent NS can receive an additional velocity ("kick") due to some still unclear processes which disrupt the spherical symmetry during the collapse or later dichotomous behavior, leading to kicks. We apply the core-collapse NS Maxwellian distribution of kick velocity $v_{\rm k}$ which is given by

$$P(v_{\rm k}) = \sqrt{\frac{2}{\pi}} \frac{v_{\rm k}^2}{\sigma_{\rm k}^3} \, {\rm e}^{-v_{\rm k}^2/2\sigma_{\rm k}^2}. \tag{1}$$

Simulations were carried out for velocity dispersion $\sigma_{\rm k} = 265\,{\rm km\ s^{-1}}$ (Hobbs et al. 2005) and $190\,{\rm km\ s^{-1}}$ (Hansen & Phinney 1997) in different cases.

2.2 Evolution of Spin Period

The evolution of spin period is directly determined by the interaction of a rotating magnetized NS with its surrounding matter. Using the model of NS evolution elaborated by Lipunov et al. (1992), Lü et al. (2010, submitted) simulated the detailed evolution of $P_{\rm s}$. Here, we apply their descriptions.

Spin evolution (spin-up or spin-down) of an NS in a binary system can be conveniently written in the form of an angular momentum conservation equation

$$\frac{{\rm d}(I\omega)}{{\rm d}t} = K_{\rm su} - K_{\rm sd}\,, \tag{2}$$

where I is the NS moment of inertia, ω is the spin frequency, and $K_{\rm su}$ and $K_{\rm sd}$ are the spin-up and spin-down torques, respectively.

A rotating magnetized NS interacting with its surrounding matter can be characterized by several basic evolutionary stages: an ejector phase, a propeller phase and an accretor phase. Lipunov et al. (1992), Dai et al. (2006) and Lü et al. (2010, submitted) have given detailed descriptions. For the spin evolution in the ejector and propeller phases, we use the model in Lipunov et al. (1992) and Lü et al. (2010, submitted).

When the fast rotating magnetic field cannot prevent matter from accreting onto the NS surface, the NS magnetic field channels the accreted material toward the magnetic poles of the NS. In the accretor stage, both torques $K_{\rm su}$ and $K_{\rm sd}$ are determined by the geometry of the accretion flow. In the wind-fed X-ray binaries, the physical condition for the formation of the accretion disk is

$j_\mathrm{a} > j_\mathrm{K}(R_\mathrm{A})$, where $j_\mathrm{a} = k_\mathrm{w}\Omega_\mathrm{b}R_\mathrm{G}^2$ is the specific angular momentum of the captured stellar wind matter, $\Omega_\mathrm{b} = 2\pi/P_\mathrm{orb}$ is the orbital frequency, $R_\mathrm{G} = \frac{2GM_\mathrm{NS}}{v_\infty^2}$ is the radius of the gravitational capture (the Bondi radius), k_w is the numerical coefficient which we set here to be 1/4 after Illarionov & Sunyaev (1975), and $j_\mathrm{K}(R_\mathrm{A}) = \sqrt{GM_\mathrm{NS}R_\mathrm{A}}$ is the Keplerian angular momentum in the NS magnetosphere. Here, R_A is the Alfvén radius, which is given by

$$R_\mathrm{A} = [\mu^2/(\dot{M}_\mathrm{NS}\sqrt{2GM_\mathrm{NS}})]^{2/7}, \tag{3}$$

where $\dot{M}_\mathrm{NS}$ is the accretion rate onto the NS. The magnetic dipole moment $\mu = B_\mathrm{NS}R_\mathrm{NS}^3/2$; B_NS and R_NS are the magnetic field and the radius of the NS, respectively. If the accretion disk is formed, the case of wind-fed disk accretion is achieved, otherwise, the quasi-spherical accretion regime is established. In this study, we assume that the disk accretion via the Roche lobe is similar to the wind-fed disk accretion.

For quasi-spherical accretion, the spin-up torque is determined by the specific angular momentum of the captured matter, i.e. $K_\mathrm{su} = \dot{M}_\mathrm{NS}k_\mathrm{w}\Omega_\mathrm{b}R_\mathrm{G}^2$. Illarionov & Kompaneets (1990) suggested that the spin-down torque depends on the NS spin frequency and the magnetospheric radius as

$$K_\mathrm{sd} = \dot{M}_\mathrm{NS}\, k_\mathrm{sd}\, \omega R_\mathrm{A}^2. \tag{4}$$

The total torque is given by

$$K = \dot{M}_\mathrm{NS}k_\mathrm{w}\Omega_\mathrm{b}R_\mathrm{G}^2 - \dot{M}_\mathrm{NS}k_\mathrm{sd}\omega R_\mathrm{A}^2, \tag{5}$$

where the model-dependent numerical coefficient k_sd is set to its maximum possible value $k_\mathrm{sd} = 2/3$ (see Shakura 2010, in preparition). When $K = 0$, the P_s^eq is given by

$$P_\mathrm{s}^\mathrm{eq} = \frac{k_\mathrm{sd}}{k_\mathrm{w}} P_\mathrm{orb} \left(\frac{R_\mathrm{A}}{}R_\mathrm{G}\right)^2 \tag{6}$$

for quasi-spherical accretion.

If accretion onto the compact star occurs via Roche lobe overflow through the vicinity of the inner Lagrangian point or $j_\mathrm{a} > j_\mathrm{K}(R_\mathrm{A})$, an accretion disk must be formed (unless the component which donates mass turns out to be inside the magnetosphere of the compact object; this case can be relevant for the accretion onto a magnetized white dwarf, as in the AM Her system). The spin-up torque in both accretor and super-accretor stages is determined by the specific angular momentum at the inner disk radius and is $K_\mathrm{su} = \dot{M}_\mathrm{NS}\sqrt{GM_\mathrm{NS}R_\mathrm{A}}$. The spin-down torque for disk accretion can be written in all cases where $K_\mathrm{sd} = (1/3)\mu^2/R_\mathrm{c}^3$, where the corotation radius $R_\mathrm{c} = [GM(P_\mathrm{s}/2\pi)^2]^{1/3}$. The torque exerted on an NS in the accretor or super-accretor stage is

$$K = \dot{M}_\mathrm{NS}\sqrt{GM_\mathrm{NS}R_\mathrm{A}} - 1/3\mu^2 R_\mathrm{c}^{-3}. \tag{7}$$

When the net torque $K = 0$, the accretion torque and the angular momentum loss due to magnetic forces lead to an equilibrium state. The equilibrium accretion period is

$$P_\mathrm{s}^\mathrm{eq} = 1.16 M_\mathrm{NS}^{-3/4}\, \dot{M}_\mathrm{NS,-8}^{-1/2}\, \mu_{30}\, R_\mathrm{A,\,8}^{-1/4}\ \mathrm{s}, \tag{8}$$

where $\mu_{30} = \mu/10^{30}$ G cm^3, $\dot{M}_\mathrm{NS,-8} = \dot{M}_\mathrm{NS}/10^{-8}\, M_\odot\ \mathrm{yr}^{-1}$, and $R_\mathrm{A,8} = R_\mathrm{A}/10^8$ cm, respectively.

2.3 Magnetic Field Decay

Because the magnetic field affects the evolution of spin periods, we must consider its change. For the decay of the magnetic field of an accreting NS, there does not yet exist a commonly accepted model. Goldreich & Reisenegger (1992) considered a decrease of the magnetic field due to Ohmic decay. From the statistical analysis of 24 binary radio pulsars, van den Heuvel & Bitzaraki (1995) discovered a clear correlation between the magnetic field and the mass accreted by the NS. In our study, we assume that the magnetic field depends exponentially on the amount of accreted matter (ΔM) and use the formula suggested by Osłowski et al. (2009)

$$B_{\rm NS} = (B^{\rm i}_{\rm NS} - B_{\rm min}) \exp\left(-\frac{\Delta M}{M_{\rm B}}\right) + B_{\rm min}, \tag{9}$$

where $B^{\rm i}_{\rm NS}$ is the initial magnetic field of the NS, $M_{\rm B}$ is the magnetic decay mass scale and $B_{\rm min}$ is the minimal magnetic field of the NS. We set $M_{\rm B} = 0.025\,M_\odot$ and $B_{\rm min} = 10^8$ G.

3 RESULTS

Because the kick velocity of the nascent NS determines whether the binary can survive, the parameter of velocity dispersion $\sigma_{\rm k}$ has an effect on the population of HMXBs. In this work, we pay attention to this effect, and take $\sigma_{\rm k} = 190$ and 265 km s^{-1} in cases 1 and 2, respectively.

3.1 Initial Input Parameters

For initial mass function, mass-ratios, and separations of components of binary systems, we adopt the descriptions used in a series of papers (Lü et al. 2006, 2008, 2009; Zhu et al. 2009). We assume that all binaries initially have circular orbits. After a supernova, the new parameters of the orbit are derived using standard formulae (Hurley et al. 2002).

We assume that the magnetic field of the nascent NS is distributed between 10^{11} and 10^{13} G according to a lognormal law. The initial spin period of a neutron star equals 10 ms. Our model is normalized to form one binary with $M_1 \geq 0.8\,M_\odot$ per year. We use 10^8 binary systems which gives a statistical error for our Monte Carlo simulation lower than 3 percent for HMXBs.

3.2 Population of HMXBs

In this work, a binary is selected as a HMXB if it satisfies the following conditions: (i) The binary includes an NS and a normal star with a mass higher than 10 $M_\odot$; (ii) There is an NS accreting matter from its companion and its mass-accretion rate is higher than $10^{-12}\,M_\odot$ yr^{-1}. The X-ray luminosity of the accreting NS can be approximated by

$$L_{\rm x} = \eta c^2 \dot{M}_{\rm NS} \simeq 5.7\times10^{35}\ {\rm erg\ s^{-1}}(\tfrac{\eta}{0.1}) \times (\tfrac{\dot{M}_{\rm NS}}{10^{-10}M_\odot\ {\rm yr}^{-1}}), \tag{10}$$

where $\eta \simeq 0.1$ is the efficiency of accretion onto the NS. This means the X-ray luminosity of HMXBs in our work is higher than $\sim 5\times10^{33}$ erg s^{-1}. We estimate the Galactic number and birthrate of HMXBs. Their number is 190 in case 1 ($\sigma_{\rm k} = 190$ km s^{-1}) and 240 in case 2 ($\sigma_{\rm k} = 265$ km s^{-1}). Correspondingly, the birthrate is between 5.9×10^{-5} yr^{-1} and 6.3×10^{-5} yr^{-1} in cases 1 and 2. In our model, the parameter $\sigma_{\rm k}$ has a weak effect. According to the catalog in Liu et al. (2006), there are 114 HMXBs in the Galaxy. Our result is close to that derived from observations. More than 95% of HMXBs have quasi-spherical accretion because the early-type massive stars have high stellar wind velocity which results in low $j_{\rm a}$.

Figure 1 shows the distribution of orbital periods in HMXBs. There are distinct regions in our observational sample: One region has $P_{\rm orb} \lesssim 10$ d while the other region has $P_{\rm orb} \gtrsim 10$ d. Similarly, there are two peaks in cases 1 and 2. The progenitors of HMXBs have usually undergone a great deal of mass transfer before the formation of the resulting NSs. When matter is transferred from one star to the other, the orbital period changes. The left peak at $\sim 6\,\mathrm{d}$ comes from the binaries in which the amount of matter transferred between the primary and the secondary is small and the initial orbital periods are shallow. Although our result agrees with the observations for the distribution of orbital periods, as discussed in Section 3.3, our model can only explain HMXBs with long orbital periods.

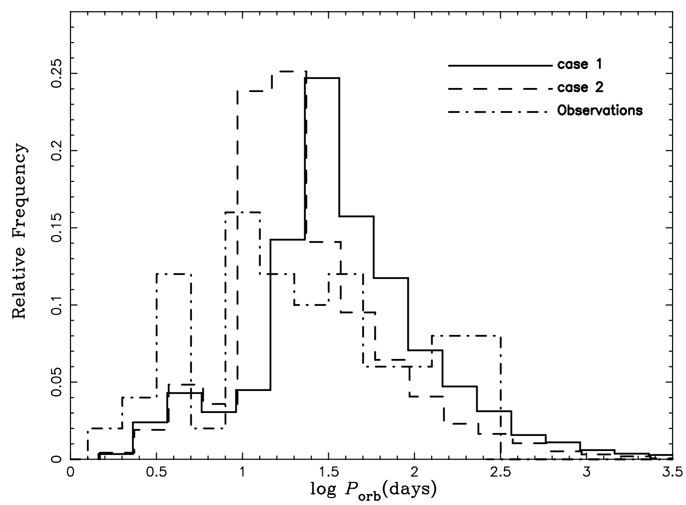

Fig. 1 Distribution of the orbital periods in HMXBs. The observational data come from Liu et al. (2006).

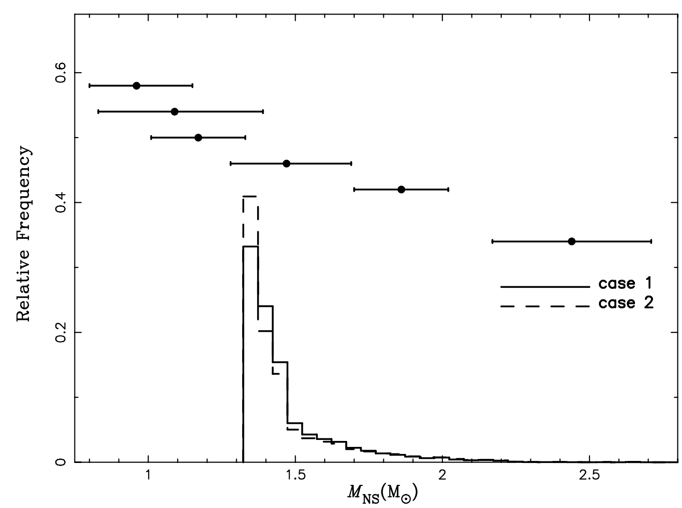

Fig. 2 Mass distribution of NSs in HMXBs. Different cases are represented by different lines. The NS masses estimated in six HMXBs come from Lattimer & Prakash (2007).

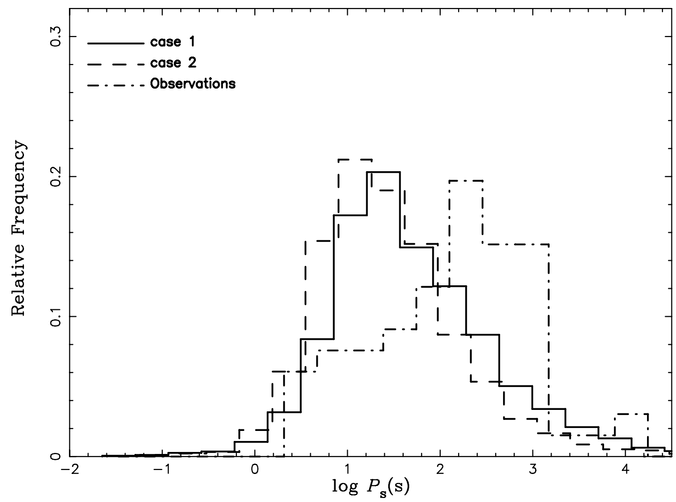

Fig. 3 The number distribution of NS spin periods in HMXBs.

Figure 2 shows the mass distribution of NSs in HMXBs. The range of NS masses in our result is between $\sim 1.3\,M_\odot$ and $2.0\,M_\odot$; there is no HMXB in which an NS has mass lower than $1.3\,M_\odot$. However, Lattimer & Prakash (2007) gave the observationally estimated masses of NSs in six HMXBs in which three HMXBs have NSs with masses lower than $1.3\,M_\odot$. It is very difficult to measure the stellar mass, and the absolute errors of measuring NS masses in Lattimer & Prakash (2007) are larger than $0.16\,M_\odot$. In general, mass estimates typically assume orbital inclinations of $i = 90°$ or are limited by i, hence the estimates are lower limits. At the same time, the stellar theory cannot give an accurate mass of the NS. Based on Figure 2, the observations may underestimate these NS masses, or the stellar theory used in our work may overestimate the NS masses.

Figure 3 shows the distribution of NS spin periods in HMXBs. As Figure 3 shows, our results cover the observations. However, the peak of $P_{\rm s}$ in our sample is at ~ 15 s and the observational one is at ~ 200 s. The main reason is that we use a very simple spherical stellar wind from massive stars. The mass transfer from massive stars to NSs in HMXBs is very complex. Details are in Section 3.3.

3.3 Corbet Diagram: $P_{\rm orb}$ vs. $P_{\rm s}$

Corbet (1986) found that the positions of HMXBs in the $P_{\rm orb}$ vs. $P_{\rm s}$ diagram are divided into three regions and correlate well with other physical properties. Regarding observations, HMXBs are divided into three groups: (i) HMXBs with relatively long orbital periods (longer than 15 d) and Be stars, which are called Be/X-ray binaries (BeXs); (ii) HMXBs with long spin periods (hundreds of seconds), relatively short orbital periods and OB supergiants, which are called supergiant/X-ray binaries (SuXs); (iii) HMXBs with short spin periods (several seconds) and short orbital periods (a few days). The majority of the known HMXBs are BeXs, and only a few are the third type of HMXB.

Figure 4 gives distributions of $P_{\rm orb}$ vs. $P_{\rm s}$ for the cases studied and observations. Our results can explain BeXs, but cannot be applied to SuXs or the third type of HMXB. SuXs are believed to be HMXBs in which the NSs directly accrete wind from supergiants without a stable accretion disk. However, with very short orbital periods (several days), it is very difficult for a massive star to evolve into a supergiant in our model. The third type of HMXB is believed to be composed of HMXBs in which mass donors are very close to filling their Roche lobes and mass-transfer rate is enhanced. NSs accrete matter via disks. In our work, one of the conditions for disk formation is the mass donors filling their Roche lobes. When mass donors in HMXBs fill their Roche lobes, HMXBs

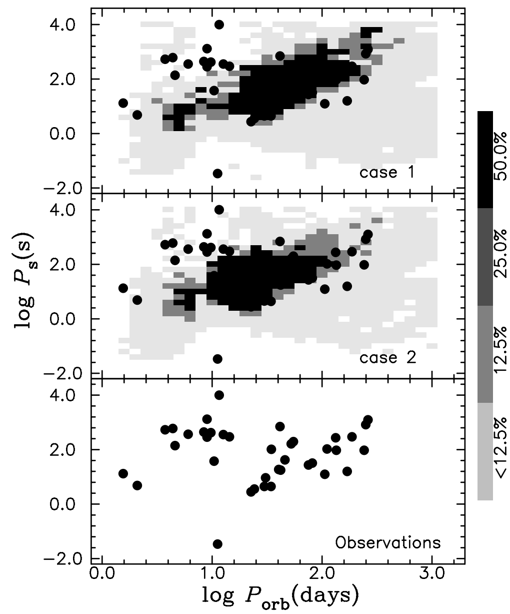

Fig. 4 Corbet diagram: Distributions of $P_{\rm orb}$ vs. $P_{\rm s}$. The observational data come from Liu et al. (2006).

undergo dynamically unstable mass transfer. The duration is very short. We hardly obtain any of this type of HMXB from our model. Our results only completely explain BeXs. However, one should note that Be stars in BeXs are usually the most rapidly rotating B stars, and they show two types of intrinsic mass loss (Bhattacharya & van den Heuvel 1991): (i) by a spherical stellar wind, and (ii) by mass ejection from their equatorial region which is presumably rotationally driven. As Section 2.2 mentioned, the evolution of $P_{\rm s}$ depends on accretional geometry. The stellar wind structure is too simple in our model.

4 CONCLUSIONS

Using a population synthesis code and simulating the evolution of spin periods for magnetized NSs which interact with their environment in binary systems, we investigate the Galactic population of HMXBs. There are 190 – 240 HMXBs in the Galaxy, and their birthrate is between 5.9×10^{-5} yr^{-1} and 6.3×10^{-5} yr^{-1}. Our model can simulate the positions of BeXs in the $P_{\rm orb}$ vs. $P_{\rm s}$ diagram, but cannot be applied to SuXs and HMXBs with short spin periods (several seconds) or short orbital periods (a few days). The main reason is that we simplify the stellar wind structure of massive stars and the process of mass transfer. Therefore, in order to understand the whole population of HMXBs, it is necessary to simulate the real structure of stellar wind and the process of mass transfer.

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