EXPLORATION OF THE $P_s$-$P_{\text{orb}}$ RELATION FOR WIND-FED X-RAY PULSARS

HAI-LANG DAI, XI-WEI LIU, AND XIANG-DONG LI

Department of Astronomy, Nanjing University, 22 Hankou Road, 210093 Nanjing, China;
hdai@nju.edu.cn, liuxw@nju.edu.cn, lixd@nju.edu.cn

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ABSTRACT

We have investigated the relation between the orbital periods ($P_{\text{orb}}$) and the spin periods ($P_s$) of wind-fed X-ray pulsars in high-mass X-ray binaries (HMXBs), based on population synthesis calculations of the spin evolution of neutron stars during the pre-HMXB stage. We show that most neutron stars either have steady accretion or still reside in the radio pulsar phase when the donor star starts to evolve off the main sequence. In the former case, the spin period can be decelerated to $\sim10^2$–$10^3$ s, depending on the value of $P_{\text{orb}}$. We briefly discuss possible origins of the $P_s$-$P_{\text{orb}}$ correlation in Be/X-ray binaries and the existence of HMXBs with main-sequence donors. We also investigate the evolution of the inclination angle between the magnetic and spin axes of neutron stars in a massive binary, suggesting secular alignment of the magnetic and spin axes during their evolution.

Subject headings: stars: early-type — stars: evolution — stars: neutron — X-rays: binaries

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1. INTRODUCTION

High-mass X-ray binaries (HMXBs) can roughly be divided into two types, in which either a supergiant star or a Be star is contained. The X-ray source often is a pulsar and powered by accretion of the material offered by the companion star. In the supergiant systems, either Roche lobe or stellar wind accretion occurs, while in the Be systems only the latter process commonly takes place, since the Be star is well inside its Roche lobe (Tauris & van den Heuvel 2006).

The relation between the spin periods $P_s$ and the orbital periods $P_{\text{orb}}$ of HMXBs was first studied by Corbet (1984, 1985, 1986), who pointed out that there may be a $P_s \propto P_{\text{orb}}^4$ correlation for neutron stars in systems with radially expanding winds, whereas $P_s \propto P_{\text{orb}}^2$ for Be systems. Van den Heuvel & Rappaport (1987) noted that the spin and orbital periods agree reasonably well with the former correlation for supergiant systems in which the X-ray source is powered by stellar wind accretion. The $P_s$-$P_{\text{orb}}$ relation has been studied by Stella et al. (1986) in terms of the equilibrium spin period at which the corotation radius is equal to the magnetospheric radius, defined by equating the ram pressure of accreting matter with the magnetic pressure of the dipole field of the neutron star (e.g., Davidson & Ostriker 1973; Lamb et al. 1973). However, in order to obtain quantitative agreement between the predicted and observed spin periods for a given orbital period, the assumption of equilibrium spin periods requires a mass accretion rate $2$ orders of magnitude lower than observed for supergiant systems (Stella et al. 1986). Waters & van Kerkwijk (1989) presented a comprehensive explanation of the $P_s$-$P_{\text{orb}}$ relation for HMXBs. For supergiant systems, they suggested that the difference between the required and the observed mass accretion rates can be explained by assuming that the present-day period is the equilibrium spin period for the stellar wind of the optical star when it was still on the main sequence (MS). The $P_s$-$P_{\text{orb}}$ correlation for Be/X-ray binaries was suggested to result from an equilbrium spin realized by virtue of the interaction between the neutron star’s magnetic field and the Be star’s equatorial wind—the wider orbits expose the neutron stars to a lower wind density on average and, hence, a lower accretion rate. The latter point was criticized by King (1991), who proposed that the observed $P_s$-$P_{\text{orb}}$ relation was probably the result of an earlier evolutionary stage, as for supergiant binaries. By calculating the angular momentum carried by the material in a Be star’s wind, Li & van den Heuvel (1996) showed that for Be/X-ray binaries in relatively narrow orbits ($P_{\text{orb}} \lesssim 100$ days), the equilibrium spin could be reached by means of angular momentum transfer via a disk formed in the equatorial wind of the Be star; in wider binaries, the low angular momentum of the wind material prevents the formation of an accretion disk, and the neutron star’s spin remains close to its previous equilibrium value from an earlier evolutionary stage. Zhang et al. (2004) have calculated the detailed spin evolution of a wind-fed neutron star in an OB binary prior to the HMXB phase, by simulating the time development of the mass-loss rate and radial expansion of a $20 M_{\odot}$ donor star.

The investigations mentioned above were usually either semi-analytic or numerical and only for individual cases. To better understand the distribution of HMXBs in the $P_s$-$P_{\text{orb}}$ diagram, an evolutionary population synthesis that incorporates the evolution of the neutron star’s spin is needed. In the present paper, we describe a Monte Carlo population synthesis study of the spin evolution of a neutron star in a massive binary. Because of the large theoretical uncertainties regarding the formation and evolution of HMXBs, our work is limited to the spin evolution of neutron stars prior to the HMXB phase. The theoretical considerations are described in § 2. The calculated results are presented in § 3, and their implications for accretion processes in HMXBs are discussed in § 4.

2. MODEL

2.1. Spin Evolution

We consider a $1.4 M_{\odot}$ magnetized neutron star in a binary system with a massive MS companion. We adopt a simplified version of the theoretical model outlined by Davies & Pringle (1981) to calculate the neutron star’s spin evolution before steady accretion occurs, as briefly described below.

Case 1: The pulsar phase.—The neutron star first appears as a rapidly rotating radio pulsar after its birth in a supernova explosion, provided that its radiation is strong enough to expel the wind material coming from the companion star beyond the radius of the
light cylinder, \( r_c = c P_0 / 2 \pi \), or the Bondi accretion radius \( r_G = 2GM/v_{\infty}^2 \) (Bondi & Hoyle 1944), where \( G \) is the gravitational constant, \( M \) is the mass of the neutron star, and \( v_{\infty} = 10^8 \text{cm s}^{-1} \) is the relative wind velocity at the neutron star’s orbit. The neutron star spins down as a result of magnetic dipole radiation, particle emission, or both:

\[
\dot{I} \Omega_s = - \frac{2 \mu^2 \Omega_s}{3 c^3},
\]

where \( I \) is the moment of inertia, \( \mu = 10^{30} \mu_{30} \text{ G cm}^3 \) is the magnetic dipole moment, and \( \Omega_s \) is the angular velocity of the neutron star.

The pulsar phase will break down under two distinct circumstances:

(a) The pulsar phase will cease if the wind material penetrates inside \( r_c \); the resulting \( P_s \) is derived by balancing radiation pressure from the pulsar with the stellar wind ram pressure at \( r_c \):

\[
P_s \simeq 0.8 \mu_{30}^{1/3} M_1^{1/6} [M/(1 M_\odot)]^{1/3} v_8^{-5/6} \text{ s}
\]

(case of Davies & Pringle 1981), where \( M = 10^{15} M_\odot \text{ g s}^{-1} \) is the rate of mass flow onto the neutron star.

(b) The pulsar phase will end when pressure gradients become important as the outer boundary \( R_c \) of the envelope, where the density \( \rho \simeq \rho_c \), approaches \( r_G \), that is, when \( R_a \simeq r_G \). The corresponding \( P_a \) is

\[
P_a \simeq 1.2 M_1^{-1/4} \mu_{30}^{1/2} v_8^{-1/2} \text{ s}
\]

(Davies & Pringle 1981).

**Case 2: The propeller phase.**—The propeller phase follows the pulsar phase. During this period, the magnetospheric radius \( R_m = [\mu^4/(2GM^2)]^{1/7} \) is larger than the corotation radius \( R_c = (GM/\Omega_s^2)^{1/3} \). The plasma interacts with the neutron star’s magnetosphere, but further accretion is inhibited by the centrifugal barrier, and the infalling matter is accelerated outward, taking away the angular momentum of the neutron star. Though the propeller effect has been investigated extensively, there remain large uncertainties about the efficiency of angular momentum loss during the propeller regime (see, e.g., Pringle & Rees 1972; Illarionov & Sunyaev 1975; Davies & Pringle 1981; Wang & Robertson 1985; Ikhsanov 2001). Here we assume that the infalling material is ejected with the corotation velocity at \( R_m \), and the spin-down torque is

\[
N = I \dot{\Omega}_a = - \dot{M} R_m^2 \Omega_a
\]

(Wang & Robertson 1985; Jiang & Li 2005). The typical spin-down timescale \( \tau = [\Omega_a / \dot{\Omega}_a] \) can be estimated to be

\[
\tau \simeq 2.2 \times 10^4 \mu_{30}^{-8/7} M_1^{3/7} [M/(1 M_\odot)]^{2/7} I_{45} \text{ yr}.
\]

The process of spinning down continues until \( P_s \) reaches the equilibrium spin period,

\[
P_{eq} \simeq 17 \mu_{30}^{6/7} M_1^{3/7} [M/(1 M_\odot)]^{-5/7} \text{ s},
\]

and we assume that steady accretion takes place afterward (but see Arons & Lea 1976; Elsner & Lamb 1976).

The spin period of the neutron star may be further changed after \( P > P_{eq} \) in the subsequent accretion phase, but we stop the calculations when either \( P_{eq} \) is reached within the MS lifetime or the companion star evolves off the MS (so that strong wind accretion or Roche lobe overflow occurs) (see also Waters & van Kerkwijk 1989). In this work we do not consider narrow HMXBs with Roche lobe overflow (such as SMC X-1, Cen X-3, and LMC X-4), in which the neutron stars are most likely to accrete from an accretion disk. For wind-fed systems such as Vela X-1, numerical calculations (e.g., Fryxell & Taam 1988; Matsuda et al. 1992; Anzer & Börner 1995; Ruffert 1999) suggest that there is no significant angular momentum transfer onto the neutron star when radially expanding wind material accretes onto the neutron star. This may result in only small deviations from the instantaneous (equilibrium, if reached) spin periods at the beginning of the accretion phase. Observations by the Burst and Transient Source Experiment on the Compton Gamma-Ray Observatory have shown a random walk in the spin frequencies, with alternating spin-up and spin-down (Bildsten et al. 1997). The spin evolution of Be/X-ray pulsars presents a completely different picture and is be discussed separately below.

### 2.2. Evolution of the Inclination Angle

Besides the spin evolution, we have considered the evolution of the inclination angle \( \chi \) between the spin and magnetic axes in wind-fed neutron stars. This part of our work is partially motivated by Bulik et al. (2003). By analyzing the light curves of 89 accretion-powered pulsars, these authors obtained an upper limit of \( \chi < 50^\circ \), suggesting that the magnetic axis tends to be aligned with the rotation axis. Similar analyses have also been conducted by Wang & Welter (1981), Leahy (1991), and Leahy & Li (1995), with similar conclusions being reached.

More recently, Blay et al. (2005) presented contemporaneous high-energy and radio observations of the HMXB 4U 2206+54 conducted with the International Gamma-Ray Astrophysics Laboratory and the Very Large Array, which firmly indicate that 4U 2206+54 hosts a magnetic, accreting neutron star. The absence of pulsations in this case is most likely due to a geometric effect, with the inclination angle of the neutron star being so small that no pulsations can be detected.

Wang & Robnik (1982) showed that the inclination angle in a binary X-ray pulsar will vary as a result of its interaction with the surrounding plasma, becoming smaller and larger during spin-down and spin-up, respectively. According to their equations (27), (36c), and (37c), we can derive the rate of change of \( \chi \) as follows:

\[
\dot{\chi} = \begin{cases} 
N \cot \chi / H \Omega_a, & \text{if } \chi \geq \theta_c, \\
3N \sin \chi / (H \Omega_a \tan^2 \chi), & \text{if } \chi \leq \theta_c,
\end{cases}
\]

where \( \theta_c \) is the critical value of the meridional angle measured from the north magnetic pole.

### 2.3. Evolution of the Mass-Flow Rate onto the Neutron Star

We employed an evolutionary population synthesis method to investigate the distribution of the orbital periods and companion masses for the natal neutron star binaries (i.e., at the moment when the neutron star was born). We started with a large set of primordial binaries and generated the systems that evolved to contain a neutron star and an MS companion. The initial mass function from Kroupa et al. (1993) was taken for the mass of the primary star (the progenitor of the neutron star, of mass \( M_1 \)). For the secondary star (of mass \( M_2 \)), we assumed a uniform distribution of the mass ratio, \( 0 < q \equiv M_2/M_1 \leq 1 \). A uniform distribution in \( \log a \) was also taken for the binary separation \( a \). We adopted the binary population synthesis code developed by Hurley et al.
(2000, 2002) to evolve the primordial binaries. This code incorporates evolution of single stars with binary star interactions, such as mass transfer, mass accretion, common-envelope (CE) evolution, collisions, supernova kicks, tidal friction, and angular momentum loss mechanisms. Most of our adopted parameters are the same as the standard ones described by Hurley et al. (2002). The star formation rate parameter is $S = 7.6085 \, \text{yr}^{-1}$, corresponding to a rate of $\sim 0.02 \, \text{yr}^{-1}$ for core-collapse supernovae (SNe) in our Galaxy under the assumption that all stars with masses above $8 \, M_\odot$ die as SNe. During the SN explosions, we apply a Maxwellian distribution for the kick velocities, with a mean of 265 km s$^{-1}$, imparted to the newborn neutron stars (Hobbs et al. 2005).

The treatment of Roche lobe overflow mass transfer in the primordial binary is presented specifically by Hurley et al. (2002), and here we briefly describe the stability criteria for mass transfer. Mass transfer by means of Roche lobe overflow takes place on either a nuclear, thermal, or dynamical timescale, depending on whether the primary remains in thermal equilibrium as it loses mass, and the radius of the primary increases faster than the Roche lobe. Stars with deep surface convective zones—for example, giants or naked helium giants—are generally unstable to dynamical-timescale mass loss and will enter a CE evolution. The stable mass accretion rate of the secondary star is limited by the Eddington accretion rate. (The secondary may actually be spun up and become a Be star when it accretes enough mass. This circumstance, however, is not included in our considerations, since the origin of Be phenomena is still unclear and it is difficult to model the mass transfer processes in Be/X-ray binaries.) The CE parameter $\alpha$ was set to 1 as a typical value, and we varied it from 0.1 to 2 in the calculations (Dewi & Tauris 2000; Tauris & Dewi 2001). Our product is a set of “incipient” neutron stars in massive binaries with a particular distribution of $P_{\text{orb}}$ and $M_2$ (shown in Fig. 1). Other binary parameters, such as the radii, surface temperatures, and luminosities of the companion stars, can also be obtained. These parameters were then used to evaluate the mass-loss rates from the companion stars and the mass flow rates onto the neutron stars.

For comparison with the observed properties of HMXBs, our calculations are limited to systems with $P_{\text{orb}} < 1000$ days and $10 \, M_\odot \leq M_2 \leq 30 \, M_\odot$. The mass-loss rate $\dot{M}_2$ was estimated with the prescription described by Nieuwenhuijzen & de Jager (1990):

$$-\dot{M}_2 = 9.6 \times 10^{-15} \frac{R_2^{0.81} L_2^{1.24} M_2^{0.16}}{P_2^2} \, M_\odot \, \text{yr}^{-1},$$

where $R_2$ and $L_2$ are the radius and luminosity of the companion star. All the quantities in equation (8) are evaluated in solar units. Assuming that the stellar wind expands isotropically at a speed $v_w$, the wind density $\rho_w$ at the orbit of the neutron star is

$$\rho_w = -\dot{M}_2 / (4\pi a^2 v_w),$$

and the mass flow rate onto the neutron star is roughly given by

$$\dot{M} = \pi r_G^2 \rho_w v_\infty$$

(Bondi & Hoyle 1944).

3. RESULTS

We calculated the evolution of spin and inclination for $6 \times 10^5$ neutron star binary systems based on the theoretical model presented in § 2. For the initial neutron star magnetic fields $B$, we assumed that log $B$ is distributed normally with a mean of 12.5 and a standard deviation of 0.3. No field decay was considered. The initial distribution of the inclination angle $\chi$ was randomly distributed in the interval $(0, \pi/2)$. We set the initial spin periods to be distributed uniformly between 10 and 100 ms, although they have little influence on the final results. We stopped our calculations when either $P_s$ reached $P_{\text{crit}}$ or the companion star began to evolve off the MS, for the reasons described above.

The calculated results are presented in Figures 2–5. The left and right panels of Figures 2 and 3 correspond to relative wind velocities at the neutron star’s orbit of $v_8 = 1$ and $v_8 = 2$, respectively. Figure 2 shows the final distribution of all the binaries in a $P_s$-$P_{\text{orb}}$ diagram. The relative numbers of binary systems are indicated by the darkness of the shading. According to our calculations, we find that when $v_8 = 1$ around 68% of the neutron
stars can reach the equilibrium period to allow wind accretion within the MS lifetime, \( t_{\text{MS}} \), while the rest would still be in either the pulsar (\( \sim 31\% \)) or the propeller (\( \sim 1\% \)) phase. This can be seen clearly in Figure 2, where the two former groups of neutron stars occupy distinct upper and lower shaded regions. The small number of stars in the propeller phase originate from its much shorter duration (Davies & Pringle 1981). If \( v_8 \) is increased to 2, the mass flow rates onto the neutron stars are lowered by a factor of \( \frac{1}{16} \) in accordance with equations (9) and (10), further extending the spin-down time in the pulsar phase. So, the corresponding

Fig. 2.— Distribution of neutron star binaries in the \( P_8-P_{\text{orb}} \) diagram when \( P_8 = P_{\text{eq}} \) or at the time \( t_{\text{MS}} \). The gray scale denotes the relative numbers in different regions. The left and right panels correspond to \( v_8 = 1 \) and \( v_8 = 2 \), respectively.

Fig. 3.— The \( P_8-P_{\text{orb}} \) distribution of wind-fed HMXBs. The dashed and solid lines represent lower limits for the spin periods for supergiant and Be systems, respectively. Asterisks and diamonds mark the Be and supergiant wind-fed HMXBs, respectively, and crosses are for Roche lobe overflow systems. The left and right panels correspond to \( v_8 = 1 \) and \( v_8 = 2 \). [See the electronic edition of the Journal for a color version of this figure.]
numbers become 42%, 55%, and 3%, respectively. The larger wind velocity also induces longer equilibrium periods. Figure 2 reveals that up to half of the neutron stars in binary systems cannot reach the equilibrium period, indicating that there might be hundreds of “sleeping” neutron star–MS star binaries such as PSR B1259+63 in the Galaxy (see also Fig. 4 below). These could be observed as radio pulsars or in X-rays depending on whether the interaction between the neutron star and the companion’s wind has become active. Most would have $P_s \sim 1$ s and $P_{\text{orb}}$ from tens to hundreds of days.

To compare the calculated results with observations of HMXBs, we show the distributions of those neutron star binaries with $P_s \geq P_{\text{eq}}$ and of the observed HMXBs in Figure 3. Asterisks and diamonds mark the Be and supergiant wind-fed HMXBs, respectively, and crosses are for Roche lobe overflow systems (data from Raguzova & Popov 2005). We first discuss the persistent, supergiant systems. Obviously, the spin periods of neutron stars can approach $P_{\text{eq}}$ if the total spin-down timescale $t_{\text{spin}}$ is less than the MS lifetime $t_{\text{MS}}$ of the companion star. As argued above, for these types of systems the current spin periods are likely to be around the equilibrium periods $P_{\text{eq}}/(\text{MS})$ attained during the MS stage because of the inefficient transfer of angular momentum during the accretion phase. For these systems to be observed as HMXBs, the accretion rate must have increased enough for the spin periods to be larger than the (current) equilibrium period $P_{\text{eq}}/(\text{sg})$ when the companion star becomes a supergiant (Stella et al. 1986; Waters & van Kerkwijk 1989); this boundary is plotted as the dashed lines in Figure 3, according to equation (6). Here we take $M_2 = 20 M_\odot$, $M_2 = 10^{-6} M_\odot$ yr$^{-1}$, and $\mu_{30} = 3$ (Coburn et al. 2002) as typical values for the supergiant systems. This period roughly serves as the lower limit for the $P_s$ of the neutron stars in supergiant HMXBs. Moreover, since the mass accretion rates generally decrease with $P_{\text{orb}}$, only those in narrow orbits ($P_{\text{orb}} \lesssim 15$ days) can have X-ray luminosities $\geq 10^{36}$ ergs s$^{-1}$ as observed.

Be/X-ray binaries generally have much longer orbital periods than the supergiant systems and are usually transient X-ray sources observable during outbursts. The structure of the Be stars’ winds is quite complicated, consisting of a relatively dense, slowly expanding, disklike, equatorial wind and a fast, isotropically expanding, polar wind (Waters & van Kerkwijk 1989). Waters & van Kerkwijk suggested that the $P_s$-$P_{\text{orb}}$ correlation for Be/X-ray binaries could be explained by setting $P_s = P_{\text{eq}}$ obtained in the disk winds. However, the current understanding of Be disk winds (Okazaki & Negueruela 2001) is very different from the radial wind model used by Waters & van Kerkwijk (1989). The evolution of the Be stars’ disks and the high eccentricities of the orbits also mean that the mass flow rates onto neutron stars in Be systems are always highly variable on both long- and short-term timescales. Because of these complications, we did not calculate...
the spin evolution of neutron stars accreting from the disk winds but, instead, present constraints on their possible locations in the $P_s-P_{\text{orb}}$ diagram. We first note that the calculated $P_{\text{eq}}(\text{MS})$, under the assumption of isotropic winds, can be regarded as the upper limit for the $P_s$ of Be/X-ray binaries, since $M$ is much lower from the polar winds than from the disk winds (these values should be taken as averaged ones, since we have ignored the eccentricity of the Be star binaries). Then, similarly to the supergiant systems, we can set the lower limit for $P_s$ for Be/X-ray binaries to be the equilibrium period $P_{\text{eq}}(\text{disk})$ in outbursts, when the disk winds dominate accretion. From the observed data for 36 Be/X-ray binaries compiled by Raguzova & Popov (2005), we have derived a correlation between the maximum luminosities and the orbital periods,

$$\log \left( \frac{L_{\text{X, max}}}{10^{35} \ \text{ergs s}^{-1}} \right) = 4.53 \pm 0.66 - (1.50 \pm 0.33) \times \log \left( \frac{P_{\text{orb}}}{\text{1 day}} \right). \quad (11)$$

Inserting equation (11) and $\mu_{50} = 3$ into equation (6), we obtain

$$\log P_{\text{eq}}(\text{disk}) \approx -0.29 + 0.64 \log [P_{\text{orb}}/(1 \ \text{day})], \quad (12)$$

which is plotted as the solid line in Figure 3. One can see that a large fraction of Be/X-ray binaries lie between $P_{\text{eq}}(\text{MS})$ and $P_{\text{eq}}(\text{disk})$. The peculiar location of A0535–669 (asterisk, lower center) may be due to its relatively low magnetic field.

The cumulative luminosity distributions of HMXBs based on our population synthesis calculations are shown in Figure 4 for different values of the parameters $\alpha$, $v_8$, and $\sigma$. The results indicate that changes in these parameters do not significantly influence the final outcomes, which are roughly compatible with the observed luminosity distributions of HMXBs in our Galaxy (Grimm et al. 2002).

In Figure 5, we plot the distribution of inclination angles for X-ray pulsars in HMXBs. It is easily seen that most of the inclination angles are within 1 radian, in general agreement with the analysis of the observational data (Bulik et al. 2003). The evolution of the inclination angle seems to be insensitive to the value of the relative wind velocity.

4. DISCUSSION

We have calculated the spin evolution of neutron stars in massive binary systems. The main idea in this work is twofold: First, to appear as X-ray binaries, the spin periods of the neutron stars should be longer than the current (instantaneous) equilibrium periods. Second, to satisfy this condition the neutron stars should be longer than the current (instantaneous) equilibrium period for Be/X-ray binaries, since X-ray pulsars in HMXBs. It is easily seen that most of the inclination angles are within 1 radian, in general agreement with the analysis of the observational data (Bulik et al. 2003). The evolution of the inclination angle seems to be insensitive to the value of the relative wind velocity.

Our preliminary results are subject to many uncertainties and the simplified treatment adopted. In the case of isotropic wind accretion, a considerable fraction of neutron stars can reach $P_{\text{eq}}$ when the companion star is still on the MS. The specific number is determined not only by the binary evolutionary processes, but also critically by the propeller mechanism. The spin-down torque (eq. [4]) adopted in this work is among the most efficient ones (Jiang & Li 2005 and references therein), and the results should be taken to be the most optimistic. For less efficient spin-down torques, the number of binaries in the propeller phase will obviously increase as a result of the longer spin-down timescales. The magnitude of $P_{\text{eq}}$ depends on the mass-loss rate, the wind velocity, and the magnetic field strength of the neutron star. With the mass-loss rates given by equation (9) and typical magnetic fields of $\sim 3 \times 10^{12}$ G, the neutron star’s spin can be decelerated to $\sim 10^{2} - 10^{3}$ s within the MS lifetime of the secondary star. The very long period, $P_s = 10^4$ s, of 2S 0114+650 (Hall et al. 2000), however, may be explained by an ultrastrong initial magnetic field ($B = 10^{14}$ G), allowing it to be spun down efficiently by the propeller effect (Li & van den Heuvel 1999).

The structure of Be star winds is much more complex and variable than that in supergiant systems, and simple propeller spin-down may not be applicable to these systems. It is likely that the $P_s$-$P_{\text{orb}}$ distribution and correlation of Be/X-ray binaries result from a balance between the spin-up during outbursts and spin-down during quiescence. Assuming that the spin-up and spin-down torques are $M_s(GM_s/\rho_m)^{1/2}$ and $-M_q R_q^2 \Omega_q$, respectively, we can derive the following expression for the equilibrium period:

$$P_{\text{eq}} = 2\pi \left( \frac{GM}{R_{m,o}^2} \right)^{-1/2} \left( \frac{M_q R_q^2}{M_{m,o}^2} \right) \left( \frac{I_q}{I_o} \right) \propto \tilde{M}_o^{-3/7} \left( \frac{M_o}{M_q} \right)^{3/7} \left( \frac{I_q}{I_o} \right) \quad (13)$$

(see also Menou et al. 1999). Here the subscripts $o$ and $q$ denote quantities evaluated during outbursts and quiescence, respectively. All three terms on the right-hand side of equation (13) are likely to increase with $P_{\text{orb}}$, which might account for the observed $P_s$-$P_{\text{orb}}$ correlation in Be/X-ray binaries.

Our calculated results also indicate the existence of HMXBs with MS donors in the Galaxy. These systems, as the progenitors of supergiant HMXBs, are less luminous than the latter (but with similar spin periods). Figure 4 suggests that there could be a few hundred of these sources in the Galaxy with X-ray luminosities ranging from $\sim 10^{33}$ to $10^{35}$ ergs s$^{-1}$. (If the propeller effect is not considered, the total number of X-ray binaries, most of which are Be/X-ray binaries, can reach a few thousand.) The HMXB 4U 2206+54 is likely to be the prototype of this kind of source (Ribó et al. 2006). A number of authors have also suggested that some neutron stars receive low kick speeds of $\lesssim 50$ km s$^{-1}$ at birth (Pfahl et al. 2002; Podsiadlowski et al. 2004; Dewi et al. 2005). If all the neutron stars were born with such small kicks, our calculations indicate that there should have been about 4–5 times more X-ray sources produced.

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