Donors of Persistent Neutron-Star Low-Mass X-Ray Binaries

CHUNHUA ZHU,1,2 GUOLIANG LU,2 ZHAOJUN WANG,2 AND NA WANG1

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ABSTRACT. Properties of X-ray luminosities in low-mass X-ray binaries (LMXBs) mainly depend on donors. We have carried out a detailed study of donors in persistent neutron-star LMXBs (PLMXBs) by means of a population synthesis code. PLMXBs with different donors have different formation channels. Our numerical simulations show that more than 90% of PLMXBs have main-sequence (MS) donors, and PLMXBs with red giant (RG) donors via stellar wind (wind) are negligible. In our model, most of the neutron stars (NSs) in PLMXBs with hydrogen-rich donors form via core-collapse supernovae, while more than 90% of the NSs in PLMXBs with naked helium star (He) donors or white dwarf (WD) donors form via an evolution-induced collapse or accretion-induced collapse for an accreting ONeMg WD. PLMXBs with different donors have different properties. In PLMXBs with MS donors, the orbital periods are between ~1 hr and 100 hr, and the mass transfer is driven by donor evolution or magnetic braking. Our population synthesis code shows that their X-ray luminosities are mainly around $10^{36}$ ergs s$^{-1}$. Similarly, in PLMXBs with RG donors via Roche lobe overflow (Roche), the mass transfer is driven by donor evolution, but orbital periods are between ~10 hr and 1000 hr. Their X-ray luminosities are $10^{37}$ ergs s$^{-1}$. The two known LMXBs (Cyg X-2 and GX 13 + 1) can belong to PLMXBs with RG (Roche) donors. PLMXBs with RG (wind) donors have the longest orbital periods and low X-ray luminosities ($10^{33}$ ergs s$^{-1}$). Their contributions to X-ray luminosities can be negligible. In PLMXBs with He donors, the orbital periods are shorter than 80 minutes, and the mass transfer is mainly driven by magnetic braking. Results of our numerical simulations predict that PLMXBs with X-ray luminosities of $10^{38}$ ergs s$^{-1}$ mainly come from binaries with He donors. In PLMXBs with WD donors, the orbital periods are shorter than 1 hr, and the mass transfer is mainly driven by gravitational radiation. According to results of our population synthesis code, their X-ray luminosities are between $6 \times 10^{35}$ and $10^{39}$ ergs s$^{-1}$, and most of the LMXBs with WD donors are transient.

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) were discovered nearly 50 years ago, and there are now ~200 known in the Galaxy (Liu et al. 2007). LMXB is a mass-transferring binary system with a compact object accretor (a black hole or a neutron-star [NS]) and a low-mass ($\leq 1 M_\odot$) donor. The X-ray luminosity function is an important characteristic of the LMXBs and has become a key tool for studying LMXBs.

Using results of Chandra observations of old stellar systems in 11 nearby galaxies of various morphological types and the census of LMXBs in the Galaxy, Gilfanov (2004) suggested that the total number of LMXBs and their combined luminosity are proportional to the stellar mass of the host galaxy. Postnov & Kuranov (2005) suggested that the flattening of the LMXBs luminosity function at lower than $2 \times 10^{37}$ ergs s$^{-1}$ might correspond to the transition from the magnetic stellar wind braking to the gravitational wave braking mechanism. Revnivtsev et al. (2011) suggested that LMXBs with X-ray luminosities below $2 \times 10^{37}$ have unevolved secondary companions, while systems with higher X-ray luminosity predominantly harbor giant donors.

In theoretical work, it is usually assumed that the X-ray luminosity is directly proportional to the mass accretion rate of compact stars in LMXBs. The mass accretion rate depends on the orbital period, donor’s evolution, and angular momentum loss. The donor is usually a main sequence (MS) or a white dwarf (WD), and it may also be a red giant (RG) or a naked helium (He) star. The properties of LMXBs are closely related to their donors. If donors are hydrogen-poor stars (WD or He), LMXBs usually are ultracompact X-ray binaries whose orbital periods are shorter than 80 minutes (Nelson et al. 1986). If donors are RGs, LMXBs are called symbiotic X-ray binaries (Masetti et al. 2006). As of now, there are about a dozen ultracompact X-ray binaries and about 10 symbiotic X-ray binaries.

Different types of stars have different properties and evolutions. Therefore, the donors in LMXBs determine orbital period and angular momentum loss, which directly affect the mass transfer rate from the donors to NSs. Obviously, the donors really determine the luminosity of LMXBs. Simultaneously,
the observational luminosity function of LMXBs provides important constraints for our simulating donors’ evolutions.

On observations, LMXBs are divided into transient and persistent sources. It is difficult to estimate the X-ray luminosities of transient LMXBs during quiescent state and outburst state. In this article, we focus on persistent LMXBs (PLMXBs) with accreting NS and different donors, and we investigate their properties and contributions to total X-ray luminosity. In § 2 we present our assumptions and describe some details of the modeling algorithm. In § 3 we discuss the main results. In § 4 the main conclusions are given.

2. MODELS

For the simulation of binary evolution, we use rapid binary star evolution code BSE (Hurley et al. 2002) with updates by Kiel & Hurley (2006). BSE code calculates the orbital changes of binary systems via mass variations, gravitational radiation, and magnetic braking. Details are in Hurley et al. (2002, § 2).

Forming channels of LMXBs are important questions in X-ray astronomy. There are many studies in the literature to investigate them (e.g., Bhattacharya & van den Heuvel 1991; Podsiadlowski et al. 2002; Pfahl et al. 2003; Lin et al. 2010). The difficulty in a theoretical investigation involves two problems: (1) keeping the binary bound when the massive progenitor of NS explodes in a supernova event and (2) a common-envelope (CE) phase. They have great effects on LMXBs. The following two subsections give descriptions.

2.1. Common-Envelope Evolution

In a binary system, due to orbital angular momentum loss or stellar expansion, a star can overflow its Roche lobe. If the mass ratio of the components \( q = M_{\text{donor}}/M_{\text{accretor}} \) at the onset of Roche lobe overflow is larger than a certain critical value \( q_c \), the mass transfer is dynamically unstable and results in the formation of a CE. The issue of the criterion for dynamically unstable Roche lobe overflow, \( q_c \), is still open. Based on the polytropic models, Webbink (1988) gave \( q_c \) for red giants as

\[
q_c = 0.362 + \frac{1}{3(1 - M_c/M_{\text{donor}})},
\]

where \( M_c \) is the core mass of the donor. However, this \( q_c \) is obtained under conservative Roche lobe overflow. Han et al. (2001, 2002) showed that \( q_c \) depends heavily on the assumed mass transfer efficiency. They found that \( q_c \) almost linearly increases with the amount of the mass and momentum lost during mass transfer. In Han et al. (2002) the critical mass ratio \( q_c \) is between 1.1 and 1.3. In this work, we take \( q_c \) as given in Eq. (1), \( q_c = 1.2 \), and \( q_c = 2.0 \) in different simulations.

Although many efforts have been devoted to understanding the evolution of CE (e.g., Ricker & Taam 2008; Ge et al. 2010; Deloye & Taam 2010), the knowledge about it is still poor. It is generally assumed that the orbital energy of the binary is used to expel the envelope of the donor with an efficiency \( \alpha_{\text{ce}} \), which is called the \( \alpha \)-algorithm. Nelemans et al. (2000) suggested to describe the CE evolution by an algorithm based on the equation for the system orbital angular momentum balance that implicitly assumes the conservation of energy (Webbink 1984), which is called the \( \gamma \)-algorithm. Following Lü et al. (2006), for CE evolution in different simulations we use \( \alpha_{\text{ce}}\lambda_{\text{ce}} = 1.0 \) in the \( \alpha \)-algorithm and \( \gamma = 1.5 \) in the \( \gamma \)-algorithm. Here, \( \lambda_{\text{ce}} \) is a structure parameter that depends on the evolutionary stage of the donor.

2.2. Formation Channels of Neutron Stars and Kick Velocity

In X-ray binaries, NSs can be formed via three channels (e.g., Ivanova et al. 2008; Kiel et al. 2008):

1. Core-collapse supernovae (CCSN) for a star with main-sequence mass \( M/M_\odot \geq 11 \).
2. Evolution-induced collapse (EIC) of a helium star with a mass between 1.4 and 2.5 \( M_\odot \) in which the collapse is triggered by electron capture on \(^{20}\text{Ne}\) and \(^{24}\text{Mg}\) (Miyaji et al. 1980).
3. Accretion-induced collapse (AIC) for an accreting ONeMg WD whose mass reaches the Chandrasekhar limit. Response of accreting ONeMg WD is treated in the same way as the evolution of CO WD (see details in Lü et al. 2009).

Nascent NS receives additional velocity (“kick”) due to some still unclear process that disrupts spherical symmetry during the collapse or later Dichotomous nature of kicks which was suggested quite early by Katz (1975). Observationally, the kick is not well constrained due to numerous selection effects. Currently, high kicks (\(~100 \text{ km s}^{-1}\) ) are associated with NS originating from CCSN, while low kicks (\(~10 \text{ km s}^{-1}\) ) with NS born in EIC and AIC (Pfahl et al. 2002).

We apply the following to core-collapse NS Maxwellian distribution of kick velocity \( v_k \):

\[
P(v_k) = \frac{\sqrt{2}}{\pi \sigma_k^3} e^{-v_k^2/2\sigma_k^2}.
\]

where \( \sigma_k = 190 \) and 400 km s\(^{-1}\) for CCSN, while \( \sigma_k^* = 20 \) and 10 km s\(^{-1}\) for EIC and AIC in different simulations.

2.3. X-Ray Luminosity

The X-ray luminosity of the accreting NS can be approximated by

\[
L_{\text{bol}} = \eta \dot{M}_{\text{NS}} c^2 = 5.7 \times 10^{35} \text{ ergs s}^{-1} \left( \frac{\eta}{0.1} \right) \left( \frac{\dot{M}_{\text{NS}}}{10^{-9} \dot{M}_\odot \text{ yr}^{-1}} \right),
\]

where \( \eta \approx 0.1 \) is the efficiency of accretion onto the NS and...
\( \dot{M}_{\text{NS}} \) is the mass accretion rate of the NS. Super-Eddington accretion rates may be important in the formation of low-mass X-ray binaries and millisecond pulsars (Webbink & Kalogera 1997). We assume that \( \dot{M}_{\text{NS}} = \min(\dot{M}_{\text{NS}}, \eta_{\text{Edd}} \times \dot{M}_{\text{Edd}}) \), where \( \dot{M}_{\text{Edd}} \) is the Eddington limit, given by

\[
\dot{M}_{\text{Edd}} = 2.08 \times 10^{-3}(1 + X)^{-1} R_{\text{NS}} M_\odot \text{ yr}^{-1}. \tag{4}
\]

Here, \( X \) is the hydrogen mass fraction, and \( \eta_{\text{Edd}} \) is the factor to allow super-Eddington luminosities, taken to be 5 (Begelman 2002; Zuo & Li 2011). To transform the bolometric luminosity into the X-ray luminosity, a bolometric correction factor \( \eta_{\text{bol}} \) is introduced by \( L_X = \eta_{\text{bol}} L_{\text{bol}} \). Following Belczynski et al. (2008), we take \( \eta_{\text{bol}} = 0.55 \).

Roche overflow-fed systems are subject to a thermal disk instability and may appear either as persistent or transient X-ray sources, depending on the mass transfer rate. A system becomes a transient X-ray source when the mass transfer rate falls below a certain critical value, \( \dot{M}_{\text{crit}} \). For hydrogen-rich disks (the donors are MSs or RGSs), we use the work of van Paradijs (1996). Applying equation (3) to \( \dot{M}_{\text{crit}} \) for a hydrogen-rich disk, we obtain the following:

\[
\dot{M}_{\text{crit}} = 1.8 \times 10^{15} P_{\text{orb}}^{0.07} \text{ g s}^{-1}, \tag{5}
\]

where \( P_{\text{orb}} \) is the orbital period in hours. For disks with heavier elements, we use the work of Menou et al. (2002):

\[
\dot{M}_{\text{crit}} = \begin{cases} 
5.9 \times 10^{16} M_{\text{NS}}^{-0.87} R_d^{2.02} \alpha_0^{-0.44} \text{ g s}^{-1}, & \text{He-rich} \\
1.2 \times 10^{16} M_{\text{NS}}^{-0.74} R_d^{2.21} \alpha_0^{0.42} \text{ g s}^{-1}, & \text{C-rich} \\
5.0 \times 10^{16} M_{\text{NS}}^{-0.48} R_d^{2.05} \alpha_0^{-0.15} \text{ g s}^{-1}, & \text{O-rich}
\end{cases} \tag{6}
\]

where \( R_d \) is a maximum disk radius (two-thirds of the accretor Roche lobe radius) in \( 10^{10} \) cm, and \( \alpha_0 = \alpha/0.1 \) is a viscosity parameter. If \( M_{\text{NS}} > \dot{M}_{\text{crit}} \) or there is wind-fed accretion, the system is a PLMXB whose X-ray luminosity is determined by equation (3). If \( M_{\text{NS}} < \dot{M}_{\text{crit}} \) in Roche overflow accretion, the system is a transient source. In this work we focus on PLMXBs.

3. RESULTS

We use the Monte Carlo method to simulate the initial binaries. For initial mass function, mass ratios, and separations of components in binary systems, we adopt the distributions used by us in Lü et al. (2006, 2008). We assume that all binaries have initially circular orbits. After a supernova, new parameters of the orbit are derived using standard formulae (e.g., Hurley et al. 2002). Table 1 lists all cases considered in the present work. Our model is normalized to formation of one binary with \( M_1 \geq 0.8 M_\odot \) per year (Yungelson et al. 1993). We use \( 1 \times 10^7 \) binary systems in our Monte Carlo simulations.

In this work, a binary is considered as PLMXB if it satisfies the following conditions:

1. The binary includes an NS, and its companion’s mass is lower than \( 6 M_\odot \).
2. The binary orbital period and the mass accretion rate of NS satisfy equations (5) and (6).

Here, we refer to both low- and intermediate-mass X-ray binaries as LMXBs.

3.1. Birthrates and Numbers of PLMXB Populations

In our simulations, there are \( \sim 29,000 \) (case 2) to 110,000 (case 3) PLMXBs in the Galaxy, and their birthrates are \( \sim 3.4-7.2 \times 10^{-4} \) yr\(^{-1}\). However, the number of all observed LMXBs is less than 200 (Liu et al. 2006). Pfahl et al. (2003) investigated LMXBs via CCSN and obtained birthrates for LMXBs of \( 10^{-6}-10^{-4} \) yr\(^{-1}\) and 400—70,000 LMXBs—a factor 10—1000 times higher than the observed number. Many authors suspected that the mismatch between the observed number and theoretically predicted number could be related to irradiation effects (Hameury et al. 1993; Hurley et al. 2010). In this work, we do not consider LMXBs in low states driven by irradiation-driven limit cycles. However, we still encounter the known problem of LMXBs.

Table 2 shows, NSs with different kinds of donors in PLMXBs have different formation channels. More than 90% of PLMXBs have undergone CCSN, especially PLMXBs with hydrogen-rich donors. However, more than 90% of PLMXBs with He donors or WD donors have undergone AIC and EIC. In cases 1 and 2, parameter \( \sigma_k \) is increased from 190 to 400 km s\(^{-1}\). The larger \( \sigma_k \), is, the more difficult it is for a binary to survive after CCSN. Therefore, the birthrate and number in case 2 are about one-third of those in case 1, and there are no PLMXBs with RG (wind) donors. In cases 1 and 3, different algorithms of CE are used. Usually, binary orbit after CE shortens up to \( \sim 1% \) of the initial one under the \( \alpha \)-algorithm assumption, while it approximately remains unchanged under the \( \gamma \)-algorithm assumption. Many binaries avoid merging when they are undergoing CE evolution in case 3. There are more PLMXBs in case 3 than those in case 1. Parameter \( \sigma_k^* \) is decreased from 20 to 10 km s\(^{-1}\) in case 5. AIC and EIC with \( \sigma_k^* = 20 \) km s\(^{-1}\) produce wider orbital periods than those with
...for the progenitors of PLMXBs, although some binary systems can be disturbed. Wider orbital periods provide enough separations so that the secondaries can evolve to RG and can survive after CE evolution. Therefore, PLMXBs via AIC and EIC mainly depend on the masses and the higher the mass transfer rate. The duration of PLMXBs with massive WDs is very short. As Figure 1 shows, there are two peaks in the distributions of WD masses. The left peak is at $\sim 0.03 M_\odot$, and the right peak is at $\sim 0.09 M_\odot$. The former mainly comes from the PLMXBs that will translate from persistent to transient state, because the donors in these PLMXBs have low mass-loss rates, which results in long durations. The latter mainly results from the PLMXBs that have undergone the AIC. Compared with the PLMXBs around the left peak, these PLMXBs around the right peak have short orbital periods and high X-ray luminosities. There are $\sim 600$–900 PLMXBs with WD donors. However, the duration of LMXBs with WD donors whose masses are lower than those in PLMXBs are very long ($\sim 10^{12} M_\odot$ yr$^{-1}$). Therefore, most of the LMXBs with WD donors are transient.

Unlike WDs, naked He stars are convective. The mass transfer in PLMXBs with He donors is driven by gravitational...
radiation and magnetic braking. In general, the latter is dominated (Hurley et al. 2002; Postnov & Kuranov 2005) and drives a mass transfer rate of \( \sim 10^{-7} M_\odot \text{yr}^{-1} \) in our work. The majority of He donors’ masses are between \( \sim 0.3 \) and \( 2.0 M_\odot \) (Fig. 1). Therefore, there are several thousand PLMXBs with He donors in the Galaxy. According to Table 2, the number of PLMXBs with He donors is much larger than the number of PLMXBs with WD donors. From the properties of type I X-ray bursts, in’t Zand et al. (2005) suggested that in most ultracompact X-ray binaries, the matter accumulated on NSs is helium. This is consistent with our results, although we do not discuss transient LMXBs. In the PLMXBs plotted in Figure 2, there are two ultracompact X-ray binaries (4U 1626-67 and 4U 0614 + 09) that have very evolved He donors (Nelemans et al. 2010).

3.2. Properties of PLMXBs with Different Donors

As § 1 mentions, the donors of LMXBs basically determine the orbital periods and mass transfer rates that give the X-ray luminosity. Figure 2 shows the distributions of the orbital periods and the X-ray luminosities or the mass accretion rate \( \dot{M}_{\text{NS}} \). PLMXBs with different donors have different positions in Figure 2.

Revnivtsev et al. (2011) investigated the brightest Galactic PLMXBs, which are plotted in Figure 2. They concluded that the majority of PLMXBs with X-ray luminosities below \( \sim 2 \times 10^{37} \text{ergs} \text{s}^{-1} \) have unevolved MS, while PLMXBs with higher X-ray luminosity predominantly harbor giant donor. In the panels of NS + MS in Figure 2, \( \sim 90\% \) of PLMXBs with MS donors lie in the shallow region with a X-ray luminosity of \( \sim 10^{36} \text{ergs} \text{s}^{-1} \). The irradiation of LMXBs can drive mass transfer (Podsiadlowski 1991; Büning & Ritter 2004). In this work, we do not consider the effect of irradiation. Therefore, compared with the luminosities of known PLMXBs, we may underestimate the luminosity of PLMXBs with MS donors. In the panels of NS + RG (Roche) in Figure 2, our sample covers the positions of Cyg X-2 and GX 13 + 1, which have long orbital periods. These PLMXBs can only be explained by NS + RG (Roche) systems in our simulations. Orosz & Kuulkers (1999) gave good measurements for Cyg X-2 and have derived the donor’s mass at around \( 0.6 M_\odot \). Podsiadlowski & Rappaport (2000) suggested that the donor in Cyg X-2 has a mass of around \( 0.5 M_\odot \) with a nondegenerated helium core and is burning hydrogen in a shell. That is, the donor in Cyg X-2 is a subgiant that has undergone the violent mass loss; this is consistent with ours.

Bandyopadhayay et al. (1999) reported that the spectrum of the donor in GX 13 + 1 clearly shows the features of the K5 III giant. Figure 3 gives the distributions of donors’ luminosities, and mass
transfer rates determine the X-ray luminosity. As the panels of NS\textsuperscript{+}RG (Roche) and NS\textsuperscript{+}RG (wind) in Figure 3 show, the donors’ luminosities in PLMXBs with RG (Roche) donors are much lower than those in PLMXBs with RG (wind), while the X-ray luminosities in the former are much higher than those in the latter. Therefore, it is more difficult to observe the donors’ luminosities in PLMXBs with RG (Roche) donors. We suggested that donors in Cyg X-2 and GX\textsuperscript{13}+1 are giants that fill up Roche lobes. The orbital periods and X-ray luminosities of two known symbiotic X-ray binaries (GX\textsuperscript{1}+4 and 4U\textsuperscript{1700}+24) are measured, which is plotted by triangles in Figure 2. NS\textsuperscript{+}RG (wind) systems can cover 4U\textsuperscript{1700}+24 very well, but our models cannot explain GX\textsuperscript{1}+4. A detailed investigation of symbiotic X-ray binaries is being carried out (Lü et al. 2012, in preparation).

In our simulations, the orbital periods of PLMXBs with WD or He donors are shorter than 80 minutes, and they are ultracompact X-ray binaries. About 10\%–34\% of WDs in NS + WD systems are He WDs, and 66\%–90\% are CO WDs. NS + ONeMg WD systems are negligible. As Figure 2 shows, PLMXBs with WD donors agree with observations, while PLMXBs with He donors have X-ray luminosities higher than those of observed ultracompact X-ray binaries. Nelemans et al. (2010) suggested that the two ultracompact X-ray binaries 4U 1626 − 67 and 4U 0614 + 09 have very evolved He donors, and their X-ray luminosities are 3.2 \times 10^{35} \text{ ergs s}^{-1} and 3.4 \times 10^{36} \text{ ergs s}^{-1}. In our model, the mass transfer in PLMXBs with He donors is driven by the magnetic braking, which produces the X-ray luminosity of \( \sim 10^{38} \text{ ergs s}^{-1} \). We may overestimate the work efficiency of the magnetic braking driving mass transfer. As panels of NS + WD and NS + He in Figure 3 show, the donors’ luminosities in PLMXBs with He donors are much higher than those in PLMXBs with WD donors. This difference may be a way via which we can distinguish He donors from WD donors.

Figure 4 gives the distribution of the X-ray luminosities (mass accretion rates) of NSs in PLMXBs with different donors. The X-ray luminosities between \( \sim 6 \times 10^{32} \) and \( 6 \times 10^{33} \text{ ergs s}^{-1} \) mainly come from PLMXBs with RG (wind). The X-ray luminosities between \( \sim 10^{35} \) and \( 10^{37} \text{ ergs s}^{-1} \) originate from PLMXBs with MS, RG (Roche), and WD donors, in which PLMXBs with MSs are dominated. The X-ray luminosities between \( \sim 10^{37} \) and \( 10^{39} \text{ ergs s}^{-1} \) mainly originate from
Fig. 3.—Similar to Fig. 2, but for distributions of donors’ luminosities vs. the X-ray luminosities or the mass accretion rate $\dot{M}_{\text{NS}}$ in PLMXBs.

Fig. 4.—Number distribution of the X-ray luminosities (mass accretion rates) of NSs in PLMXBs with different donors. The width of the bin for log $L_x$ (ergs s$^{-1}$) is 0.5. The dashed lines in the total panels represent the power-law X-ray luminosity function for LMXBs in Gilfanov (2004).
PLMXBs with He donors in which the mass transfer is driven by magnetic braking. Postnov & Kuranov (2005) suggested that observed X-ray luminosity function ($>2 \times 10^{37}$ ergs s$^{-1}$) of LMXBs can generally be explained by the accretion of matter onto a NS with magnetic stellar wind, which agrees with our results. However, the observed X-ray luminosity function (up to $\sim 2 \times 10^{37}$ ergs s$^{-1}$) of LMXBs can be explained by PLMXBs with MS and RG (Roche) donors. In BSE code, their X-ray luminosities are between $\sim 1$ hr and 100 hr, and the mass transfer is driven by donor evolution or magnetic braking. Our population synthesis code shows that their X-ray luminosities are mainly $\sim 10^{35}$ ergs s$^{-1}$. Similarly, in PLMXBs with RG donors via Roche lobe overflow (Roche), the mass transfer is driven by donor evolution, but orbital periods are between $\sim 10$ hr and 1000 hr. Their X-ray luminosities are $\sim 10^{37}$ ergs s$^{-1}$. The two known LMXBs (Cyg X-2 and GX 13 + 1) can belong to PLMXBs with RG (Roche). PLMXBs with RG (wind) donors have the longest orbital periods and low X-ray luminosities. Their contributions to X-ray luminosities can be negligible. In PLMXBs with He donors, the orbital periods are shorter than 80 minutes, and the mass transfer is mainly driven by magnetic braking. Results of our numerical simulations predict that PLMXBs with X-ray luminosities of $\sim 10^{35}$ ergs s$^{-1}$ mainly come from binaries with He donors, but their X-ray luminosities may be overestimated in our work.

\[ L_{X} \approx 10^{37} \frac{M_{\odot}}{C_{0}} \]

In this work we do not consider transient LMXBs with different donors. In future work, we will investigate donors in persistent and transient LMXBs, and we will discuss the X-ray luminosity function of LMXBs.

\[ L_{X} \approx 10^{39} \frac{M_{\odot}}{C_{0}} \]

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