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Asymmetric supernova explosions and the formation of short period low-mass X-ray binaries

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Abstract. We consider the formation of short period low-mass X-ray binaries using standard evolutionary scenario which involves a common envelope phase and a supernova explosion. We consider three models of systems and assume several values of the efficiency factor for the common envelope evolution ($\alpha_{\rm CE}$). In most cases the systems can only be formed if the neutron stars in the systems receive a kick velocity at their birth. We determine the lower and upper limits of the required kick velocity as a function of $\alpha_{\rm CE}$. Larger kicks are required to form shorter orbital period systems. Higher $\alpha_{\rm CE}$ also requires larger kicks. In general, the required kick velocity is of the order of a few hundred kms^{-1} with a maximum of $\sim$ 1000 kms^{-1}. The range of the required kick velocity is narrower for higher $\alpha_{\rm CE}$.

Key words: stars: supernovae: general – stars: neutron – stars: evolution – stars: binaries: general

1. Introduction

Low-mass X-ray binaries (LMXBs) are binary systems consisting of a compact star (a neutron star and a black hole) accreting matter from a low-mass ($\lesssim$ 1M$_\odot$) nondegenerate star. Many LMXBs have orbital period less than one day (White et al. 1995). We call this systems as short period LMXBs.

We will consider the formation of short period LMXBs using standard scenario which involves a common envelope (CE) evolution followed by a supernova (SN) explosion (Sutantyo 1975, see also van den Heuvel 1983, 1994). Pylyser & Savonije (1988) show that if, after the SN explosion and the tidal circularization, the orbital period ($P_{\rm orb}$) is shorter than a bifurcation period ($P_{\rm bif}$, which, according to them, is $\sim$ 0.5–1 d), angular momentum loss due to magnetic braking and gravitational radiation will drive the two components closer. On the other hand, if $P_{\rm orb} > P_{\rm bif}$, mass transfer driven by the nuclear evolution of the donor star will make the system wider. Short period LMXBs are formed if $P_{\rm orb} < P_{\rm bif}$.

In this paper we will address the nature of the SN explosion which has formed the compact star in short period LMXBs. We will only consider the case where the compact star is a neutron star. The exploding star is a helium star which is originally the helium core of the primary. Kalogera & Webbink (1998) indicate that, based on a choice of the efficiency factor of CE evolution ($\alpha_{\rm CE}$), the SN explosion could not be symmetric for the following reason. Symmetric explosion requires that the mass of the exploding star should not be too large as otherwise the system will be disrupted. However, low-mass helium star will evolve to a large radius before collapse (Arnett 1978; Habets 1985). Such an expansion can initiate a second CE phase which may abort the formation of the neutron star. To prevent the second CE phase, the post-CE (pre-SN) orbital separation should be wide enough to accomodate the expansion of the helium star. Since symmetric explosions always increase the orbital separation, the post-SN orbital separation will even be larger. This will be too large that the low-mass secondary will not reach it within $\sim 10^{10}$yr, i.e., the system will not evolve to an X-ray source within the age of the Galaxy. This leads to the conclusion that the neutron star should have been formed by asymmetric SN explosion. In this case the newly born neutron star receives a kick velocity at its birth. In this paper we will derive constraints on the required kick velocities and their dependence on the assumed $\alpha_{\rm CE}$.

In Sect. 2 we describe the evolutionary history and the formation of LMXBs and the formulas used in this paper. Constraints on the orbital parameters at each evolutionary stages are discussed in Sect. 3. We discuss the results in Sect. 4 and summarize the conclusions in Sect. 5.

2. The evolutionary scenario

2.1. Overview

According to the standard evolutionary scenario, LMXBs have originated from systems consisting of a massive ($\gtrsim$ 10M$_\odot$) primary and a low-mass ($\lesssim$ 1M$_\odot$) secondary. In a system with a sufficiently small mass ratio, the mass transfer which occurs after the primary evolves to fill up its Roche lobe is unstable. The orbit shrinks very rapidly as a consequence of the mass transfer in combination with the tidal instability. The low-mass secondary plunges into the envelope of the primary. Both stars are embedded in a common envelope. During the spiral-in of the low-mass secondary, the envelope is blown off. At the end of the CE phase, the system consists of a helium star (originally the helium core of the primary) and a low-mass secondary. As a large fraction of the orbital energy is used to expel the envelop, the orbital separation of the system is very small (a few solar radii). The helium star will eventually explode as a supernova and leave behind a compact star as a remnant. The surviving systems consists of a neutron star and a low-mass nondegenerate star in an eccentric orbit. The low-mass star is still on the main-sequence when the explosion happens. It needs 10^8 – 10^9 yr before it evolves to fill up its Roche lobe and the system becomes an X-ray source. Within this time interval tidal forces will circularize the orbit.

2.2. Common envelope evolution

During the CE evolution, the envelope of the primary is blown off at the expense of the orbital energy (Webbink 1984). Some other energy sources may also contribute to the process (Iben & Livio, 1993). To describe the amount of energy used to eject the envelope one defines the efficiency factor $\alpha_{\rm CE}$ for the CE evolution,

$$\alpha_{\rm CE} \simeq \frac{\Delta E_{\rm b}}{\Delta E_{\rm orb}} \tag{1}$$

where $\Delta E_{\rm b}$ is the binding energy of the envelope and $\Delta E_{\rm orb}$ is the difference of the orbital energy before and after CE phase. $\alpha_{\rm CE} = 1$ means that all energy required to eject the envelope is completely provided by the orbital energy. $\alpha_{\rm CE} \lesssim 1$ indicates a less efficient situation in which only a part of the orbital energy difference can be used to blow off the envelope. In this case, a larger fraction of orbital energy is required to expel the envelope, so the process will result to a tighter binary. It may also be possible that $\alpha_{\rm CE} \gtrsim 1$ if in addition to the orbital energy there are some other energy sources available to assist the ejection of the envelope, i.e. accretion energy, recombination energy, etc (cf.Iben & Livio, 1993). This is not an unlikely case, since during the giant or AGB phase, even a single star can lose its envelope without requiring binary motion in a common envelope (e.g. through stellar wind or planetary nebula process). This indicates that energy is already available in the envelope, the binary motion makes the process even easier.

Using Eq. (1) one can derive a simple relation of the orbital separation before and after the CE phase in terms of $\alpha_{\rm CE}$ as follows (Webbink, 1984),

$$\frac{a_2}{a_1} = \frac{M_{\rm He} M_2}{(M_{\rm He} + M_{\rm e})(M_2 + 2M_{\rm e}/(\lambda \alpha_{\rm CE} r_{\rm L})} \tag{2}$$

where a_1 and a_2 are, respectively, the orbital separation before and after the CE phase, $M_{\rm He}$ is the final mass of the mass losing star (i.e. the mass of the helium star), $M_{\rm e}$ is the envelope mass, M_2 is the secondary mass and $a_1 r_{\rm L}$ is the Roche lobe radius of the primary, λ is a weighting factor which depends on the density profile of the envelope, we assume $\lambda = 0.5$.

2.3. Supernova explosion

Assume that the pre-SN orbit is circular and the orbital separation between the two components is $a_{\rm o}$. Denote $M_{\rm He}$ and $M_{\rm n}$ are, respectively, the mass of the exploding star before and after the explosion, M_2 is the mass of the unexploding star. The neutron star receives a kick velocity $V_{\rm k}$. The angle between the kick velocity and the initial orbital velocity is θ, while the azimuthal angle is ϕ (ϕ =0 if the kick velocity is in the orbital plane). The impact of the SN shell transfers momentum and imparts an impact velocity $V_{\rm i}$ to the unexploding star, where,

$$V_{\rm i} = \eta (\frac{R_2}{2a_{\rm o}})^2 \frac{M_{\rm shell}}{M_2} V_{\rm shell} \tag{3}$$

R_2 is the radius of the unexploding star; $M_{\rm shell}$ and $V_{\rm shell}$ are, respectively, the mass and the velocity of the SN shell. Two dimensional hydrodynamical analyses by Fryxell & Arnett (1981) suggests that $\eta \sim$ 0.3 to 0.8. We assume that $\eta = 0.5$.

One can calculate the post-SN semi-major axis and the eccentricity from (Sutantyo 1992),

$$\frac{a_{\rm o}}{a} = 2 - YF_2 \tag{4}$$

$$(1 - e^2) = \frac{a_{\rm o}}{a} YF_1 \tag{5}$$

where Y is the ratio of the total mass before and after the explosion,

$$Y = \frac{M_2 + M_{\rm He}}{M_2 + M_{\rm n}} \tag{6}$$

and,

$$F_1 = [1 + 2v_{\rm k} cos\theta + {v_{\rm k}}^2 (cos^2\theta + sin^2\theta sin^2\phi)] \tag{7}$$

$$F_2 = (1 + 2v_{\rm k} cos\theta + {v_{\rm k}}^2 + 2v_{\rm i} v_{\rm k} sin\theta cos\phi + {v_{\rm i}}^2) \tag{8}$$

where $v_{\rm k}$ and $v_{\rm i}$ are, respectively, the ratio of the kick and the impact velocity to the initial relative orbital velocity.

2.4. Tidal circularization

The secondary is still on the main-sequence at the SN stage. It needs 10^8 – 10^9 yr before it evolves to fill up its Roche lobe and the system becomes an X-ray source. Within this time interval the tidal effects will circularize the orbit. The tidal interaction between the two components will dissipate energy from the system but will conserve the total angular momentum. If $a_{\rm cir}$ is the orbital separation at the end of the tidal circularization, then the conservation of angular momentum implies (we neglect the stellar rotational angular momentum as, at most, it is only a few percent of the total angular momentum),

$$a_{\rm cir} = a(1 - e^2) \tag{9}$$

or (using Eq. (5));

$$a_{\rm cir} = a_{\rm o} YF_1 \tag{10}$$

Note that we can relate the post circularization orbital separation directly to the pre SN orbital separations independent of the post-SN parameters as well as the effect of impact of the SN shell. Eq. (10) shows that either for very small ($v_{\rm k} \ll 1$) or very large ($v_{\rm k} \gg 1$) kick velocity, the pre-SN orbital separation tends to be shorter than that after the tidal circularization.

3. Constraints on the orbital parameters

3.1. Constraints at the initial stage

We expect that the neutron star in LMXBs have originated from a primary star with mass $\gtrsim 10\mathrm{M}_{\odot}$. Before filling its Roche lobe the star might have lost a considerable fraction of its mass in a stellar wind. Using the evolutionary models of Schaller et al. (1992), Kalogera & Webbink (1998) indicate that the primary can only fills its Roche lobe before the core helium burning or after core helium exhaustion. Roche lobe overflow between these stages is improbable as the star hardly expands upon losing mass while at the same time the Roche lobe radius increases as a result of the systemic mass loss. They also show that if the primary fills its Roche lobe before the core helium burning, the system will not evolve to an LMXB as the post-CE orbital period is too short to accomodate the expansion of the helium star. Therefore, to enable the system to evolve to an LMXB, the Roche lobe overflow should happen after the primary reaches the core helium exhaustion (case C mass transfer). From this condition one can set a lower limit to the pre-CE orbital separation (for a given mass of the primary and secondary). The upper limit can be set from the condition that the primary fills up its Roche lobe just before collapse. These lower and upper limits restrict the parameter space in primary mass – orbital separation diagram in which the system can initiate and survive the CE phase to a narrow region.

3.2. Constraints at the post-CE (pre-SN) stage

Using Eq. (2) and a chosen value of $\alpha_{\rm CE}$, constraints on the orbital separation as a function of the primary mass at the initial (pre-CE) stage can be translated to the post-CE parameter space. The upper and lower limit to the post-CE orbital separation as a function of the mass of the helium star (originally the helium core of the primary) are shown as thick and thin solid lines in Figs. 1 to 5 for $\alpha_{\rm CE}$ = 1, 2 and 4, respectively, and $M_2 = 1\mathrm{M}_{\odot}$.

As argued above, the helium star should be formed after core helium exhaustion of the initial primary. Since helium is already exhausted at the center, the helium star will have a short lifetime (10^5 yr) so that subsequent mass loss can be ignored (Kalogera & Webbink 1998). The system is not expected to change its orbital parameters until the SN explosion happens. Therefore, the above constraints at the post-CE phase can be regarded as constraints at the pre-SN stage.

Beside constraints derived from the initial stage, one can also derive constraints based on the condition that the post-CE orbit should be wide enough to accomodate the evolution of the helium star. Low-mass helium star will expand considerably before collapse (Arnett 1978, Habets 1985). If the helium star fills its Roche lobe, the system may enter a second CE-phase, a further mass loss from the helium star will happen. This may abort the formation of the neutron star (note, however, that this assumption does not directly follow from evolutionary computation, so it must be taken with precaution; a neutron star may still be formed if mass loss is not so severe). Therefore, to prevent the second CE-phase, the orbit after the first CE-phase must be wide enough to prevent the helium star to fill up its Roche lobe before collapse. There must also be enough space in the orbit to accomodate the evolution of the secondary such that it will not reach its Roche lobe before the formation of the neutron star. These give lower limits to the orbital separation as shown as dashed and dashed-dotted lines in Figs. 1 to 5.

3.3. Constraints at the post-SN stage

Kalogera & Webbink (1996) show that for a system to become an X-ray source, the post-SN orbital period must be small enough such that the low-mass ($\lesssim 1\mathrm{M}_{\odot}$) donor can fill its Roche lobe in 10^{10} yr (the age of the Galaxy). Assuming the mass of the neutron star is 1.4 $\mathrm{M}_{\odot}$, this gives an upper limit to the orbital period as a function of the donor mass (for a 1 $\mathrm{M}_{\odot}$ donor mass the upper limit is $\sim$ 0.5 d and shorter for lower-mass donor).

This time limit does not apply for larger mass donors as they will reach their Roche lobe in a time less than the age of the Galaxy. But small orbital periods are still required for such donors. A stable sub-Eddington mass transfer is expected to occur only if the donor fills its Roche lobe before ascending the giant branch. Otherwise it will result to super-Eddington mass transfer (if $1 \lesssim M_2 \lesssim 1.5\mathrm{M}_{\odot}$) or will lead to dynamical instability (if $M_2 \gtrsim 1.5\mathrm{M}_{\odot}$).

Note that this limit applies at the time mass transfer is initiated. As the system might have undergone angular momentum loss due to magnetic braking and gravitational radiation prior to the mass transfer, the post-SN orbit could be wider than this.

Pylyser & Savonije (1988) indicate that there is a bifurcation period ($P_{\rm bif}$) that if the orbital period ($P_{\rm orb}$) is shorter than the bifurcation period, the two components get closer as a consequence of angular momentum loss due to magnetic braking and gravitational radiation. On the other hand, if $P_{\rm orb} > P_{\rm bif}$, mass transfer driven by the nuclear evolution of the donor star will make the system wider. Using conservative evolution, Pylyser & Savonije derive that $P_{\rm bif} \sim$ 0.5–1 d. Ergma et al. (1998) indicate, however, that for non-conservative evolution $P_{\rm bif}$ could be as high as 1.5–1.6 d. We assume that the post-CE systems will evolve to short period LMXBs if after the tidal circularization $P_{\rm cir} \leq P_{\rm bif}$. In this paper we will use three models of systems, i.e., 1) 1 + 1.4 $\mathrm{M}_{\odot}$ with $P_{\rm cir} = P_{\rm bif}$ = 0.75 d, 2) 1 + 1.4 $\mathrm{M}_{\odot}$ with $P_{\rm cir} = P_{\rm bif}$ = 1 d, and 3) 1.5 + 1.4 $\mathrm{M}_{\odot}$ with $P_{\rm cir} = P_{\rm bif}$ = 1.5 d. Since all conclusions are also valid for systems with shorter orbital periods and/or smaller donor mass (cf. Sect. 4.2), those models can be regarded as representative for the formation of all short period LMXBs.

4. Discussion

4.1. Symmetric SN explosion

For a symmetric SN explosion, Eq. (10) can simply be written as,

$$a_{\rm cir}(M_{\rm He} + M_2) = a_{\rm o}(M_{\rm n} + M_2) \quad (11)$$

Therefore, for a given M_2, $M_{\rm n}$ and $a_{\rm cir}$, we can plot $a_{\rm o}$ as a function of $M_{\rm He}$.

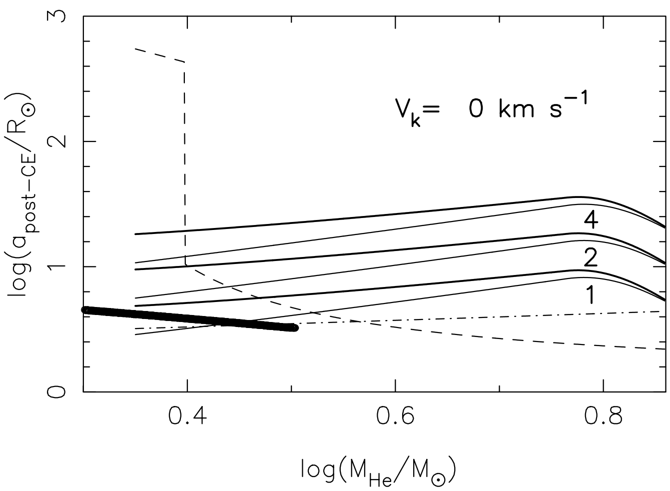

Fig. 1. Limits on the post-CE orbital separation as a function of the mass of the helium star for the second model ($M_2 = 1\mathrm{M}_\odot$, $M_\mathrm{n} = 1.4\mathrm{M}_\odot$ and $P_\mathrm{cir} = P_\mathrm{bif} = 1\,\mathrm{d}$). The lower and upper limits based on the constraints at the primordial stage are shown as *thin* and *thick solid lines* for α_CE = 1, 2 and 4, respectively. The *dashed line* indicates the lower limit that the orbit can accomodate the expansion of the helium star. The *dashed-dotted line* shows the lower limit that the low-mass secondary does not fill its Roche lobe during its main-sequence phase. The *very thick line* shows the solution for *symmetric* SN explosion.

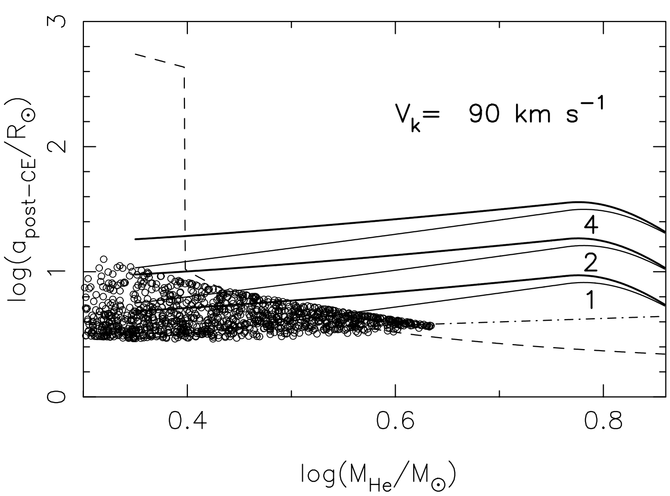

Fig. 2. Limits on the post-CE orbital separation and the solution for *asymmetric* SN explosion with $V_\mathrm{k} = 90\mathrm{kms}^{-1}$ for the second model ($M_2 = 1\mathrm{M}_\odot$, $M_\mathrm{n} = 1.4\mathrm{M}_\odot$ and $P_\mathrm{cir} = P_\mathrm{bif} = 1\,\mathrm{d}$). Line coding is the same as in Fig. 1. An isotropic distribution of the kick is assumed. Each point represents a particular direction of the kick.

Fig. 1 shows the result for system in our second model ($M_2 = 1\mathrm{M}_\odot$, $M_\mathrm{n} = 1.4\mathrm{M}_\odot$ and $P_\mathrm{cir} = P_\mathrm{bif} = 1\,\mathrm{d}$). The combination of M_2 and a_o, which produces the system is shown as a very thick line. Note that this line is far below the allowed parameter space determined by all constraints described in Sect. 3. This fact has also been shown by Kalogera & Webbink (1998) for α_CE = 2 (or α_CE =1 in their paper, since they absorp λ in α_CE; see Fig. 3 of their paper). This strongly indicates that short period low-mass X-ray binaries with donor mass of $1\mathrm{M}_\odot$

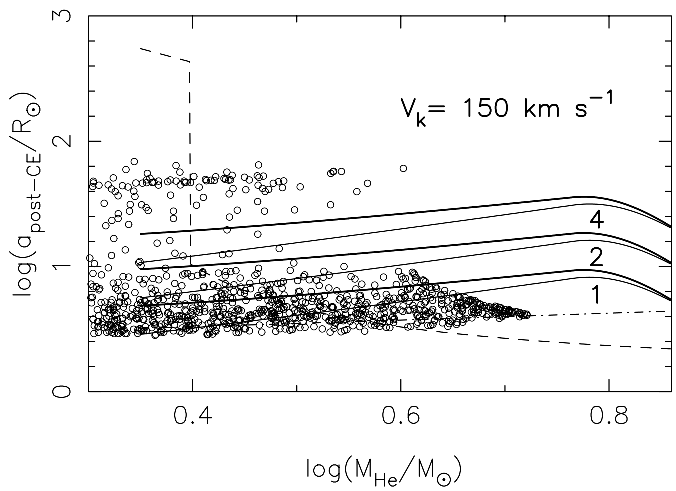

Fig. 3. Same as Fig. 2 for $V_\mathrm{k} = 150\mathrm{kms}^{-1}$.

cannot be formed through a symmetric SN explosion. The argument against symmetric SN explosion is even stronger for systems with smaller donor mass and/or smaller orbital period.

4.2. Asymmetric SN explosion

In case of asymmetric SN explosion, one can use Eq. (10) to plot a_o as a function of M_He if in addition to M_2, M_n and a_cir, the magnitude and the direction of the kick are also given. Figs. 2 to 5 show the results for V_k = 90, 150, 600 and 1100 kms^{-1}, respectively, to produce LMXBs in our second model ($M_2 = 1\mathrm{M}_\odot$, $M_\mathrm{n} = 1.4\mathrm{M}_\odot$ and $P_\mathrm{cir} = P_\mathrm{bif} = 1\,\mathrm{d}$). In these figures we take a random orientation of the kick and each point represents a particular direction. As can be seen from the figures, the plot of of a_o as a function of M_He spreads to a broader area than in the symmetric case.

We will describe the results with a particular attention to the case $\alpha_\mathrm{CE} = 2$. In Fig. 2, which show the case $V_\mathrm{k} = 90\mathrm{kms}^{-1}$, the solutions spread in an area just below the parameter space allowed by the constraints. This gives a lower limit to the kick velocity, i.e., for $\alpha_\mathrm{CE} = 2$ the system can only be formed if $V_\mathrm{k} \geq 90\mathrm{kms}^{-1}$.

Fig. 3 shows that for V_k = 150 kms^{-1} the solutions cover a larger area that makes the formation of LMXBs is entirely possible for α_CE up to ~ 16. But, as is shown in Fig. 4, increasing V_k to a larger value, 600 kms^{-1} in this case, pushes the solutions much further down again. This is because either very small or very high kicks tend to imply smaller pre-SN orbital separations (cf. Sect. 2.4). Note that in this case the solutions are moving down just below the allowed parameter space for $\alpha_\mathrm{CE} = 2$. This sets an upper limit to the kick velocity. To form the system with $\alpha_\mathrm{CE} = 2$ we require $V_\mathrm{k} \leq 600\mathrm{kms}^{-1}$.

The lower and upper limits on V_k are also valid for $P_\mathrm{cir} \leq 1\,\mathrm{d}$ and/or $M_2 \leq 1\mathrm{M}_\odot$ since the constraints on V_k are even stronger in this case (for a given V_k the solutions are even farther away down from the allowed parameter space).

Increasing the kick velocity to $1100\mathrm{kms}^{-1}$, as is shown in Fig. 5, makes the solutions moving out of the parameter space

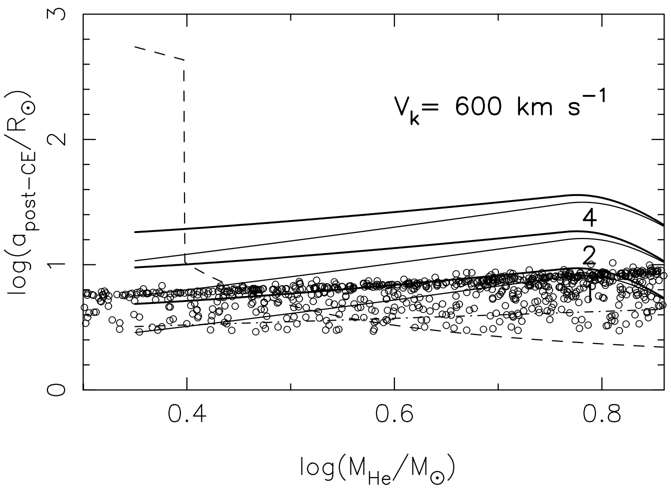

Fig. 4. Same as Fig. 2 for $V_{\rm k} = 600 {\rm kms}^{-1}$.

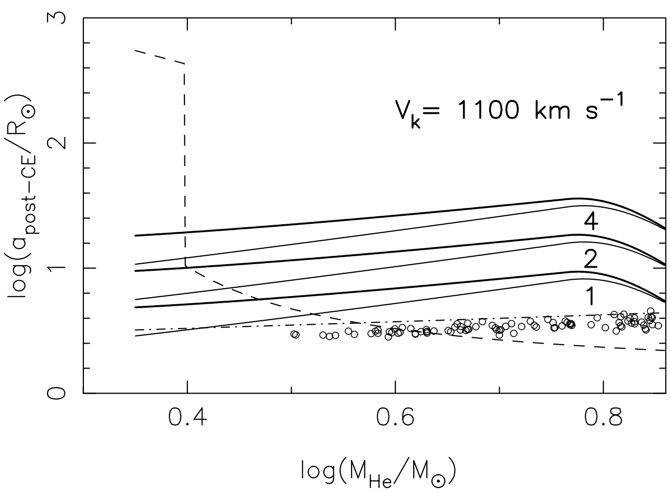

Fig. 5. Same as Fig. 2 for $V_{\rm k} = 1100 {\rm kms}^{-1}$.

allowed by all constraints. This sets an absolute upper limit to the kick velocity.

5. Conclusion

Using the method described in Sect. 4 we determine the lower and upper limits for the kick velocity required to form the system in each model. Table 1 summarizes the results and we conclude (this conclusion is independent of the effect of impact of the supernova shell, as is indicated in Eq. (10)):

1. Larger kick velocities are required to form systems with shorter orbital period.
2. Higher $\alpha_{\rm CE}$ needs higher kicks.
3. Range of the required kick velocity is narrower for higher $\alpha_{\rm CE}$.

The required kick velocities is in general of the order of a few hundred ${\rm kms}^{-1}$ with a maximum of $\sim 1000 {\rm kms}^{-1}$. This is consistent with the result of van Paradijs & White (1995) which shows that the galactic-z distribution of LMXBs can be ac-

Table 1. Range of kick velocities required to form the system.

M	$P_{\rm cir}$	$\alpha_{\rm CE}$	$V_{\rm k}$ (kms^{-1})
1 + 1.4 M$_\odot$	0.75 d	< 1	90–1050
		1	95–850
		2	110–550
		4	115–400
1 + 1.4 M$_\odot$	1 d	< 1	50–1100
		1	60–850
		2	90–600
		4	100–400
1.5 + 1.4 M$_\odot$	1.5 d	< 1	0–940
		1	15–775
		2	65–510
		4	90–360

counted if, at their birth, the neutron stars received kick velocities with a magnitude distribution represented by the observed velocity distribution of radio pulsars (with an average of $\sim 450 {\rm kms}^{-1}$, Lyne & Lorimer 1994). Population synthesis based on the disk instability model in irradiation dominated disks by Kalogera et al. (1998) suggests somewhat lower velocities, i.e., 100–200 kms^{-1}, but still within the range given in Table 1. Note, however, that *symmetric* explosion is also possible in our third model for small $\alpha_{\rm CE}$ (compare with the work of King & Kolb (1997) which also requires secondary mass of $\sim$ 1.3–1.5 M$_\odot$ for *symmetric* explosion). Symmetric explosion may also possible in other models if the condition for preventing helium star common envelope is relaxed (cf. Sect. 3.2).

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