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On the origin of the difference between the runaway velocities of the OB-supergiant X-ray binaries and the Be/X-ray binaries

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Abstract. The recent finding by Chevalier & Ilovaisky (1998) from *Hipparcos* observations that OB-supergiant X-ray binaries have relatively large runaway velocities (mean peculiar tangential velocity[1] $\langle v_{\rm tr}\rangle = 42 \pm 14$ km s^{-1}), whereas Be/X-ray binaries have low runaway velocities ($\langle v_{\rm tr}\rangle = 15 \pm 6\,{\rm km\,s^{-1}}$), provides confirmation of the current models for the formation of these two types of systems. These predict a difference in runaway velocity of this order of magnitude. This difference basically results from the variation of the fractional helium core mass as a function of stellar mass, in combination with the conservation of orbital angular momentum during the mass transfer phase that preceded the formation of the compact object in the system. This combination results into: (i) Systematically narrower pre-supernova orbits in the OB-supergiant systems than in the Be-systems, and (ii) A larger fractional amount of mass ejected in the supernovae in high-mass systems relative to systems of lower mass. Regardless of possible kick velocities imparted to neutron stars at birth, this combination leads to a considerable difference in average runaway velocity between these two groups. If one includes the possibility for non-conservative mass transfer the predicted difference between the runaway velocity of the two groups becomes even more pronounced. The observed low runaway velocities of the Be/X-ray binaries confirm that in most cases not more than 1 to 2 $\rm M_\odot$ was ejected in the supernovae that produced their neutron stars. This, in combination with the –on average– large orbital eccentricities of these systems, indicates that their neutron stars must have received a velocity kick in the range 60–250 km s^{-1} at birth. The considerable runaway velocity of Cygnus X-1 ($v_{\rm tr} = 50 \pm 15\,{\rm km\,s^{-1}}$) shows that also with the formation of a black hole considerable mass ejection takes place.

Key words: stars: binaries: close – stars: early-type – stars: emission-line, Be – stars: evolution – stars: supernovae: general – X-rays: stars

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[1] The values given here are not identical (though similar) to those listed in Chevalier & Ilovaisky (1998). The corrections we applied are outlined below.

1. Introduction

A high-mass X-ray binary (HMXB) consists of a massive OB-type star and a compact X-ray source, a neutron star or a black hole. The X-ray source is powered by accretion of wind material, though in some systems mass transfer takes place through Roche-lobe overflow; the compact stars in the latter systems are surrounded by an accretion disk. Since wind accretion plays an important role, in practice only an OB supergiant or a Be-star companion have a strong enough stellar wind to result in observable X-ray emission. In a Be/X-ray binary the X-ray source is only observed when the neutron star moves through the dense Be-star disk at periatron passage. About 75% of the known HMXBs are Be/X-ray binaries, although this is a lower limit given their transient character.

Chevalier & Ilovaisky (1998) derived the proper motions for a sample of HMXBs from *Hipparcos* measurements. The four OB-supergiant HMXBs for which proper motions are available (0114+65, 0900-40 [Vela X-1], 1700-37 and Cyg X-1) have relatively large peculiar tangential velocities. Some corrections to the values given by these authors are needed (cf. Steele et al. 1998, Kaper et al. 1999). Taking these into account (Table 1) the mean peculiar velocity of these systems is $42 \pm 14\,{\rm km\,s^{-1}}$. It was already known that the OB-supergiant system of 1538-52 (QV Nor) has a peculiar radial velocity of about $90\,{\rm km\,s^{-1}}$ with respect to its local standard of rest (Crampton et al. 1978; Gies & Bolton 1986; van Oijen 1989). For the 13 Be/X-ray binaries with measured proper motions Chevalier & Ilovaisky found peculiar tangential velocities ranging from $v_{\rm tr} = 3.3 \pm 0.7$ to $21 \pm 7.4\,{\rm km\,s^{-1}}$, with an average of $\langle v_{\rm tr}\rangle = 11.4 \pm 6.6\,{\rm km\,s^{-1}}$. Again, after corrections (see Sect. 2) and excluding the Oe systems X Per (0352+309) and V725 Tau (0535+262), one finds for the genuine Be/X-ray binary a slightly higher value of $v_{\rm tr} = 15 \pm 6\,{\rm km\,s^{-1}}$.

We would like to point out here that these mean values are in good agreement with the runaway velocities of these two types of systems predicted on the basis of simple "conservative" evolutionary models (van den Heuvel 1983, 1985, 1994; Habets 1985; van den Heuvel & Rappaport 1987) and even better agreement is obtained when mass is not conserved in the transfer process (Portegies Zwart 2000). The effect of sudden mass loss during the supernova explosion is taken into account and in a massive binary this is the dominant contribution to the runaway velocity; a random kick velocity of a few hundred $\mathrm{km\,s^{-1}}$ imparted to the neutron star at birth (see e.g. Hartman 1997) has only a small effect, as the kick's impulse has to be distributed over the entire massive ($\gtrsim 15\,\mathrm{M_\odot}$) system. (See Portegies Zwart & van den Heuvel 1999, for arguments in favor of kicks). Therefore, in first-order approximation, these kicks can be neglected in calculating the runaway velocities of HMXBs, but *not* in calculating their orbital eccentricities (see Sects. 3.4 and 3.5).

The aim of the present paper is to give a quantitative assessment of the above-mentioned conjectures. It should be noted here that five Be-star systems in the Be/X-ray binary sample studied by Chevalier & Ilovaisky (1998) are of spectral type B4 Ve or later (masses $\leq 6M_\odot$). The companions of these stars might be white dwarfs instead of neutron stars. Therefore, a supernova explosion is not necessarily the reason for their (excess) space velocity, which, in any case, is relatively small. It may be due to the typical random velocities observed in young stellar systems. Leaving these late-type Be/X-ray binaries out does not result in a significant change in the observed mean peculiar velocity of the Be-systems. Furthermore, there is some doubt concerning the use of the distances based on *Hipparcos* parallaxes of several of the other Be-systems, as these distances differ very much from the distances determined in other ways, e.g. by using reddening etc. (Steele et al. 1998). In Sect. 2 we therefore critically examine the distances and proper motions of all the systems with Be companions.

In Sects. 3.1 and 3.2 we present an analytical calculation of the expected runaway velocities and orbital eccentricities of typical OB-supergiant and Be HMXBs, on the basis of the standard evolutionary models for these systems, adopting conservative mass transfer during phases of mass exchange, and including the effects of stellar-wind mass loss for the OB-supergiant systems. In Sect. 4 we discuss the effect of non-conservative mass transfer on the runaway velocity and in Sect. 5.1 for the Be/X-ray binaries with known orbital eccentricities. We calculate which kick velocities should be imparted to the neutron stars of Be/X-ray binaries in order to produce their, on average, large orbital eccentricities (since the mass-loss effects alone cannot produce these). In Sect. 5.2, as an alternative, we compare the observed runaway velocities and orbital eccentricities of the Be/X-ray binaries with those expected on the basis of symmetric mass ejection and show that without kicks their combination of high orbital eccentricities and low space velocities cannot be explained. Our conclusions are summarized in Sect. 6.

2. The observed peculiar tangential velocities of HMXBs

The 4 OB-supergiant systems in the *Hipparcos* sample of Chevalier & Ilovaisky (1998) have distances larger than 1 kpc, which is too remote for a reliable parallax determination. For these systems they estimated the distances based on the spectral type, visual magnitude and reddening, and eventually the strength and velocity of interstellar absorption features, etc. After correcting for the peculiar solar motion and differential galactic rotation (see also Moffat et al. 1998) the *Hipparcos* proper motions result in the peculiar tangential velocities listed in Table 1. Chevalier & Ilovaisky give a mean peculiar tangential velocity of $v_{\rm tr} = 41.5 \pm 15\,\mathrm{km\,s^{-1}}$. We derive a similar value of $42 \pm 14\ \mathrm{km\,s^{-1}}$.

For the Be-systems, Chevalier & Ilovaisky use the *Hipparcos* parallaxes to determine the distances. For some systems this leads to very surprising results. In particular, Steele et al. (1998) point out that for the system of 0236+610 (LSA + $61°303$) the *Hipparcos* parallax leads to a ten times smaller distance than the distance estimated from the spectral type and reddening. These authors convincingly show that for this system the distance estimate based on the *Hipparcos* parallax cannot be correct; the distance of the system must be of order 1.8 kpc instead of the 177 pc determined from the *Hipparcos* parallax. Similarly, from a variety of criteria they find that for A0535+262 the distance must be > 1.3 kpc, instead of the 300 pc determined from the *Hipparcos* parallax. Steele et al. point out that for both systems the *Hipparcos* parallaxes are smaller than 3 times their probable (measurement) error, and are therefore not reliable. In such a case one cannot reliably use the *Hipparcos* parallax to determine the distance. With the *Hipparcos* distances the OB-star companions of 0236+610 and 0535+262 would become highly underluminous for their spectral types, and would be very peculiar stars, as was already noticed by Chevalier & Ilovaisky (1998). On the other hand, using alternative distance criteria, their absolute luminosities become perfectly normal for their spectral types. This gives confidence that the latter distances are more reliable.

The systems including a Be star with spectral type later than B4 V (mass $\leq 6M_\odot$) may well have white dwarfs instead of neutron stars as companions (Portegies Zwart 1995). Therefore, their space velocity is not necessarily caused by a supernova explosion, which is the scenario we exploit in this paper. Excluding these systems, the observed mean peculiar velocity hardly changes ($\langle v_{\rm tr}\rangle = 14.4 \pm 6.6\ \mathrm{km\,s^{-1}}$ in stead of 15 ± 6, excluding X Per and V725 Tau), and since the nature of their compact companions is not known anyway (e.g. no X-ray pulsations observed which would identify the compact star as a neutron star), we decided to leave them in the calculation of the mean peculiar velocity. The peculiar tangential velocities of X Per (0352+309, O9 III-IVe, 27 $\mathrm{km\,s^{-1}}$) and V725 Tau (0535+262, O9.7 IIe, 97 $\mathrm{km\,s^{-1}}$) are relatively high; their early spectral types suggest that they have masses comparable to those of the OB supergiants, so that, like the OB-supergiant systems, they would also originate from relatively massive binary systems. In Table 1 we list the peculiar tangential velocity for each individual system and calculate the average for different subsamples. We left out the Be star γ Cas, because its X-ray binary nature is not clear; furthermore, its X-ray spectrum is consistent with that of a white dwarf (Haberl 1995).

For the systems 0236+610, 0535+262, 1036-565 and 1145-619 the *Hipparcos* parallaxes yield absolute visual magnitudes very different from those expected on the basis of the OB-spectral types of the stars. In these cases, the *Hipparcos* parallax

Table 1. Peculiar transverse velocities (with respect to the local standard of rest) of the HMXB sample of Chevalier & Ilovaisky (1998), after correcting the distances of the four Be-systems for which the *Hipparcos* parallaxes are not significant (see text). For all systems we recalculated the corrections for solar motion and Galactic rotation.

X-ray source	Name	Spectral type	Distance d [kpc]	$v_{\rm tr}$ [km s^{-1}] $d/1.4$	d	$1.4d$
0114+650	V662Cas	B0.5 Ib	3.8	14.2	26.4	43.6
0900-403	GP Vel	B0.5 Ib	1.8	22.7	34.0	50.0
1700-377	V884Sco	O6.5 If+	1.7	46.0	58.0	74.8
1956+350	V1357Cyg	O9.7 Iab	2.5	35.3	47.4	64.5
0236+610	LSI+61°303	B0 IIIe	1.8	2.6	9.0	19.4
0352+309	X Per	O9 III-IVe	0.8	23.6	27.3	33.4
0521+373	HD34921	B0 IVpe	1.05	18.4	23.4	32.1
0535+262	V725 Tau	O9.7 IIe	2.0	73.2	96.5	129.1
0739-529	HD63666	B7 IV-Ve	0.52	9.7	12.2	16.9
0749-600	HD65663	B8 IIIe	0.4	6.9	9.9	16.0
1036-565	HD91188	B4 IIIe	0.5	18.3	20.4	23.4
1145-619	V801 Cen	B1 Ve	1.1	7.9	5.8	6.1
1249-637	BZ Cru	B0 IIIe	0.3	12.9	13.6	16.3
1253-761	HD109857	B7 Ve	0.24	17.6	23.7	33.8
1255-567	μ^2 Cru	B5 Ve	0.11	12.5	13.5	16.9

measurements are less than three times their probable errors and thus not reliable. For these stars we therefore used the distances determined from spectral type and reddening, which yield absolute visual magnitudes consistent with their spectral types.

We rederived the peculiar tangential velocities relative to the local restframe from the *Hipparcos* proper motions (cf. Kaper et al. 1999). Table 1 lists the peculiar tangential velocity corrected for the peculiar solar motion and differential galactic rotation for three different distances ($d/1.4$, d, $1.4d$, following Gies & Bolton 1986). The uncertainty in distance (and thus in peculiar motion) is difficult to estimate; therefore, we calculated the space velocity for different values of the distance. The peculiar tangential velocities for the HMXBs discussed in Clark & Dolan (1999) are identical to ours for the OB-supergiant systems, though they find different values for the Be/X-ray binaries X Per (15 ± 3 km s^{-1}, $d = 700$ pc), V725 Tau (57 ± 14 km s^{-1}, $d = 2$ kpc), and 1145-619 (17 ± 7 km s^{-1}, $d = 510$ pc). Obviously, the precise values for the peculiar motion depend on the adopted model for the galactic rotation; we used the formalism employed in Comerón et al. (1998). For the OB-supergiant systems in the sample of Chevalier & Ilovaisky (1998) also the radial velocities are available from literature. This is not the case for the Be/X-ray binary systems. Therefore, we only consider the two components of the tangential velocity for the comparison of the kinematic properties of the two groups. The table shows that, leaving the two O-emission systems out, the Be/X-ray binaries have low space velocities: 15 ± 6 km s^{-1}.

3. Runaway velocities expected on the basis of models with conservative mass transfer and symmetric mass ejection

3.1. Change of orbital period due to mass transfer

We only consider here so-called case B mass transfer since for the evolution of massive close binaries this is the dominant mode of mass transfer (cf. Paczyński 1971; van den Heuvel 1994, but see Wellstein & Langer 1999). In case B the mass transfer starts after the primary has terminated core-hydrogen burning, and before core-helium ignition. After the mass transfer in this case the remnant of the primary star is its helium core, while its entire hydrogen-rich envelope has been transferred to the secondary, which due to this became the more massive component of the system. There is a simple relation between the mass of the helium core $M_{\rm He}$ and that of its progenitor $M_\circ$(see for example van der Linden 1982; Iben & Tutukov 1985). We adopt here the relation given by Iben & Tutukov (1985):

$$M_{\rm He} = 0.058 {M_\circ}^{1.57}, \tag{1}$$

which results in a fractional helium core mass p given by:

$$p = M_{\rm He}/M_\circ = 0.058 {M_\circ}^{0.57}. \tag{2}$$

The change in orbital period of the system in case of conservative mass transfer (i.e.: conservation of total system mass $M_{\rm tot}$ and orbital angular momentum J) and initially circular orbits is (Paczyński 1971; van den Heuvel 1994):

$$\frac{P_f}{P_\circ} = \left(\frac{M_\circ m_\circ}{M_f m_f}\right)^3, \tag{3}$$

where $P_\circ$, $M_\circ$ and $m_\circ = M_{\rm tot} - M_\circ$ denote the orbital period and component masses before the mass transfer, and P_f, M_f and $m_f = M_{\rm tot} - M_f$ are the orbital period and component masses after the transfer. The transformation between orbital separation and the orbital period is given by Kepler's third law.

Introducing the initial mass ratio $q_\circ = m_\circ/M_\circ$ and using Eq. (2), Eq. (3) can be written as

$$\frac{P_f}{P_\circ} = \left(\frac{q_\circ}{p(q_o + 1 - p)}\right)^3. \tag{4}$$

Since according to Eq. (2), p increases for increasing stellar mass, one observes that, due to the third power in Eq. (4), for the same $q_\circ$ the orbital period of a very massive system increases much less as a result of the mass transfer, than for systems of lower mass. (The term $(q_o + 1 - p)$ changes much less than p itself for increasing stellar mass, so for a given q_o this term has only a modest effect.) This is the main reason for the systematically longer orbital periods of the Be/X-ray binaries (always > 16 days) relative to those of the OB-supergiant HMXBs (in all but one case: between 1.4 days and 11 days, cf. van den Heuvel, 1983, 1985, 1994). This is illustrated in Table 2 where we list the relative post-mass-transfer periods $P_f/P_\circ$ for typical Be/X-ray binary progenitor systems, with $M_\circ = 10\,\mathrm{M}_\odot$ and $12\,\mathrm{M}_\odot$, respectively, and for two typical OB-supergiant HMXB progenitors with $M_\circ = 25\,\mathrm{M}_\odot$ and $35\,\mathrm{M}_\odot$, respectively, for $q_\circ$ values ranging from 0.4 through 0.8.

3.2. *Possible effects of further mass transfer and stellar winds on the orbits*

3.2.1. Case BB mass transfer

The helium cores left by the $10\,\mathrm{M}_\odot$ and the $12\,\mathrm{M}_\odot$ stars have masses of $2.15\,\mathrm{M}_\odot$ and $2.87\,\mathrm{M}_\odot$, respectively. During helium-shell burning, when these stars have CO-cores, their outer layers may expand to dimensions of a few to several tens of solar radii, and a second, so-called Case BB, mass transfer may ensue before their cores collapse to neutron stars (Habets 1985,1986ab). However, since the radius of the $2.87\,\mathrm{M}_\odot$ helium star will not exceed 5 $R_\odot$, a second mass transfer phase is unlikely to occur here. In the case of the $2.15\,\mathrm{M}_\odot$ helium star, which does attain a large radius, the amount of mass that is in the extended envelope is not more than $0.1\,\mathrm{M}_\odot$. For these reasons, we will neglect here the effects of Case BB mass transfer, and will assume that these helium stars do not lose any mass before their final supernova explosion. This means, that we will slightly overestimate the imparted runaway velocities (as the orbits at the time of the explosion will be slightly wider than we assume, and the ejected amounts of mass will be somewhat smaller than we assume).

3.2.2. Stellar-wind mass loss in massive stars

Since wind mass-loss rates from Wolf-Rayet (WR) stars – massive helium stars– are much larger (viz.: $\gtrsim 10^{-5}\,\mathrm{M}_\odot\mathrm{yr}^{-1}$) than the mass-loss rates of lower-mass main-sequence stars, for the sake of argument (in order to include only the largest effects) we take into account the effects of the wind mass loss during the WR phase. The effects of these winds are: (1) to widen the orbits, and (2) to considerably decrease the mass of the helium ($\equiv$ WR) star before its core collapses. In the cases of the $25\,\mathrm{M}_\odot$ and $35\,\mathrm{M}_\odot$ primary stars, the masses of the helium cores are $9.1\,\mathrm{M}_\odot$ and $15.4\,\mathrm{M}_\odot$, respectively. Such stars live 9×10^5 years and 7.5×10^5 years, respectively, and are expected to lose about $4.0\,\mathrm{M}_\odot$ and $7.4\,\mathrm{M}_\odot$ through their wind during this phase of their evolution, respectively[2]

Thus, at the moment of the supernova explosion the collapsing cores of these stars will have masses of $5\,\mathrm{M}_\odot$ and $8.0\,\mathrm{M}_\odot$, respectively. To keep the same notation we will express the relative mass loss in the stellar wind with $\delta = \Delta M_{\mathrm{wind}}/M_\circ$. The value for δ is 0.16 for a primary with a mass of $25\,\mathrm{M}_\odot$ and 0.21 for a $35\,\mathrm{M}_\odot$ primary star. In the cases of no wind mass loss (in lower mass primaries): $\delta = 0$.

The wind mass loss will change the post-mass-transfer orbits as follows (van den Heuvel 1994):

$$d\log a = -d\log M_{\mathrm{tot}}, \tag{5}$$

and

$$d\log P = -2d\log M_{\mathrm{tot}}, \tag{6}$$

where a is the orbital separation and M_{tot} the total system mass.

Eq. (6) results in:

$$P/P' = \left(\frac{M'_{\mathrm{tot}}}{M_{\mathrm{tot}}}\right)^2, \tag{7}$$

where P and P' correspond to the system masses M_{tot} and M'_{tot}, respectively. M_{tot} is the total mass at the beginning of the WR phase and M'_{tot} the total system mass at the end of this phase, just prior to the supernova explosion of the WR Star. The orbital separation after mass transfer and additional WR mass loss phase is expressed as:

$$\frac{a'}{a_\circ} = \frac{a_f}{a_\circ}\frac{a'}{a_f} \equiv \left(\frac{q_\circ}{p(1+q_\circ-p)}\right)^2\left(1-\frac{\delta}{1+q_\circ}\right)^{-1} \tag{8}$$

3.3. *Runaway velocities induced by symmetric supernova mass ejection*

The runaway velocity imparted to the system by the supernova mass loss is calculated from the loss of momentum of the system during the explosion: $-V_{\mathrm{orb},1}\Delta M_{\mathrm{sn}}$, where $V_{\mathrm{orb},1}$ is the orbital velocity of the helium star prior to the explosion and ΔM_{sn} is the amount of mass ejected in the supernova.

We assume all compact remnants to be a $1.4\,\mathrm{M}_\odot$ neutron star. Then ΔM_{sn} is given by $\Delta M_{\mathrm{sn}} = (p-\delta)M_o - 1.4M_\odot$. The remaining mass of the system is:

$$M''_{\mathrm{tot}} = m_f + 1.4\mathrm{M}_\odot = (q_o + 1 - p)M_o + 1.4M_\odot. \tag{9}$$

This yields a recoil velocity (or runaway velocity) of the system of:

$$V_{\mathrm{rec}} \;=\; V_{\mathrm{orb},1}\frac{\Delta M_{\mathrm{sn}}}{(q_o+1-p)M_o + 1.4M_\odot} \tag{10}$$

Here the second term in the right argument is simply the post supernova eccentricity and we may write simply

$$V_{\mathrm{rec}} = eV_{\mathrm{orb},1} \tag{11}$$

[2] We assumed here wind mass-loss rates of $0.5 \times 10^{-5}\,\mathrm{M}_\odot\mathrm{yr}^{-1}$ for the $9.1\,\mathrm{M}_\odot$ star and $10^{-5}\,\mathrm{M}_\odot\mathrm{yr}^{-1}$ for the $15.4\,\mathrm{M}_\odot$ star, respectively. These rates are in good agreement with observed WR-wind mass-loss rates (cf. Leitherer et al. 1995), but are lower than the rates adopted by Woosley et al. (1995), which **may** overestimate the real mass-loss rates, since they give for all initial helium star masses, final masses before core collapse of only about $4\,\mathrm{M}_\odot$.

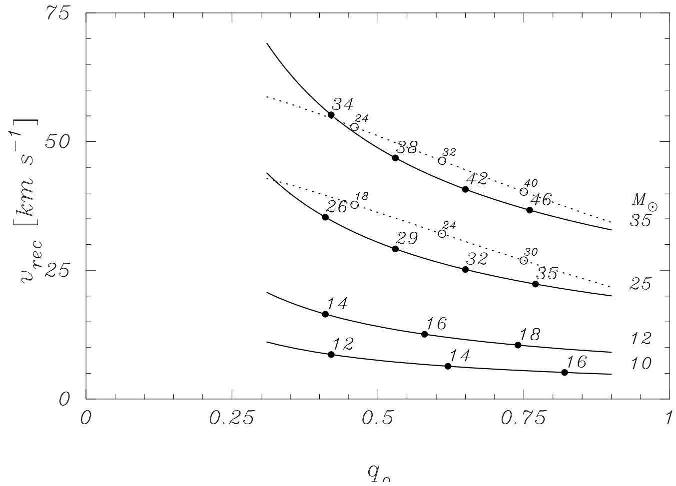

Fig. 1. The recoil velocity of X-ray binaries induced by the supernova as a function of the initial mass ratio. The initial orbital period is 5 days for all binaries. From bottom to top the solid lines represent the recoil velocities for binaries with an initial primary mass of $10\,\mathrm{M}_\odot$, $12\ \mathrm{M}_\odot$, $25\ \mathrm{M}_\odot$ and $35\ \mathrm{M}_\odot$, respectively. The numbers printed above • on the curves indicate the mass of the runaway star in $\mathrm{M}_\odot$. Mass loss in the Wolf-Rayet phase is taken into account for the top two curves ($25\ \mathrm{M}_\odot$ and $35\ \mathrm{M}_\odot$ zero-age primaries). The dotted lines show the same evolutionary calculations but relaxing the assumption that mass is conserved during transfer (see Sect. 4).

The relative orbital velocity before the explosion is $\sqrt{GM'_{\rm tot}/a'}$. One therefore has:

$$V_{\rm orb,1} = \left(\frac{GM_o}{a_o}\right)^{1/2} \frac{p(1+q_o-p)^2}{q_o(1+q_o)^{1/2}} \tag{12}$$

Substitution of Eq. (11) into Eq. (10) results now in

$$V_{\rm rec} = \left(\frac{GM_o}{a_o}\right)^{1/2} \times \frac{p(1+q_o-p)^2}{q_o(1+q_o)^{1/2}} \frac{(p-\delta-1.4M_\odot/M_o)}{(q_o+1-p+1.4M_\odot/M_o)} \tag{13}$$

which in numerical form becomes:

$$V_{\rm rec} = 212.9[\mathrm{km\,s^{-1}}]\left(\frac{M_o}{[M_\odot]}\frac{[\mathrm{days}]}{P_o}\right)^{1/3} \times\frac{p(q_o+1-p)^2(p-\delta-1.4M_\odot/M_o)(1+q_o-\delta)}{q_o(1+q_o)^{2/3}(q_o+1-p+1.4M_\odot/M_o)} \tag{14}$$

Fig. 1 shows for $P_\circ = 5$ days the values of $V_{\rm rec}$ as a function of $q_\circ$ for the four primary masses of Table 2, using the $\Delta M_{\rm sn}$ and $\Delta M_{\rm wind}$ as given above. The figure shows that for the "Be-systems" (initial primary masses $10\,\mathrm{M}_\odot$ and $12\,\mathrm{M}_\odot$ yielding Be-star masses ranging from $11.85\,\mathrm{M}_\odot$ to $18.7\,\mathrm{M}_\odot$) the expected recoil velocities range from 5 to 21 $\mathrm{km\,s^{-1}}$, whereas for the "OB-supergiant systems" (with OB-companions between $25\,\mathrm{M}_\odot$ and $40\,\mathrm{M}_\odot$) they range between 21 and $> 80\,\mathrm{km\,s^{-1}}$, respectively. These velocities correspond to transverse velocities that are $\pi/4$ times these values, i.e.: 3.9 to 17 $\mathrm{km\,s^{-1}}$ for the Be-systems, and 16.5 to $> 71\ \mathrm{km\,s^{-1}}$ for the OB-supergiant systems with neutron stars. Thus one expects average transverse velocities of order 10.5 $\mathrm{km\,s^{-1}}$ and 45 $\mathrm{km\,s^{-1}}$ for the Be/X-ray binaries and OB-supergiant systems, respectively. For both the Be/X-ray binaries and the OB-supergiant systems Be/X-ray the predicted and observed mean transverse runaway velocities agree well: $15 \pm 6\ \mathrm{km\,s^{-1}}$and 42 ± 14, respectively.

As Eq. (14) shows, the dependence of the recoil velocity on $P_\circ$ is rather weak, so for initial orbital periods between a few days and 10 days these results don't change by more than a factor 1.5. Therefore, certainly qualitatively, Fig. 1 is representative for the two types of systems. Eq. (14) further shows that the large difference in runaway velocity between the two types of systems is due to a combination of two factors, as follows: (1) the larger fractional helium core masses (p) in the more massive systems, which cause their pre-supernova orbital periods to be shorter and thus their pre-supernova orbital velocities to be larger than those of the lower-mass systems; and (2) the much lower amounts of mass ejected ($\Delta M_{\rm sn}$) in the lower mass systems compared to the systems of higher mass, which leads to a lower recoil effect.

Relaxing the assumption that mass is conserved during the phase of mass transfer changes little, which we will discuss now.

4. The effects of non-conservative mass transfer

In the above it was assumed that the case B mass transfer was conservative in all systems. For the Be-systems this "conservative" assumption seems confirmed quite straightforwardly as the Be nature is interpreted by the accretion of angular momentum and thus of mass. On the other hand, for the OB-supergiant X-ray binaries several authors (starting with Flannery & Ulrich 1977 for the Cen X-3 system) have pointed out that certainly in part of the systems the mass transfer has been non-conservative, and there is a considerable evolution for massive close binaries altogether (De Loore & De Greeve 1992). Indeed, close Wolf-Rayet binaries with high mass ratios $q = M_{\rm WR}/M_{OB}$ such as CQ Cep ($P = 1.64$ days, $q = 1.19$) and CX Cep ($P = 2.22$ days, $q = .44$) cannot have been produced by conservative evolution, and just these systems are the progenitors of the OB-supergiant X-ray binaries (cf. van den Heuvel 1994).

The amount of mass lost from the system during the transfer will depend on the initial mass ratio $q_\circ$ of the system. For small $q_\circ$ the companion will accrete little and most of the envelope mass of the primary will be lost from the system. On the other hand, for large $q_\circ$ little mass will be lost from the system. Therefore, in order to study the effect of mass and angular momentum loss on the runaway velocity, we assume as a first approximation that the fraction f of the primary's envelope which is accreted by the companion star is proportional to the initial mass ratio $q_\circ$ (Portegies Zwart 1995)

$$f = q_\circ. \tag{15}$$

After mass transfer the secondary mass then becomes

$$m_f = M_\circ + fM_\circ(1-p) \equiv M_\circ q_\circ(2-p). \tag{16}$$

The gas lost by the donor leaves with low velocity but gains angular momentum via the interaction with the companion star.

Table 2. Resulting orbital parameters and runaway velocities for a number of characteristic initial primary masses (first column) and mass ratios (second column). The increase in orbital period P_f/P_o due to the mass transfer and the mass of the OB-component of the resulting X-ray binary are listed in columns 3 and 4, respectively. Columns 5, 6, 7, 8 and 9 list for the case of symmetric supernova mass ejection: the resulting runaway velocity of the system $V_{\rm rec}$ (for an assumed initial orbital period $P_o = 5^d$), $V_{\rm rec}$ expressed as a fraction of the relative orbital velocity V_o in the initial orbit, the orbital eccentricity, the post-supernova orbital period P''_f/P_o, and the runaway velocity in the postsupernova system, f_v, as defined by Eq. (22), respectively.

$M_\circ$ [$M_\odot$]	$q_\circ$	$\frac{P_f}{P_o}$	m_f [$M_\odot$]	$V_{\rm rec}$ [a] [km s^{-1}]	$V_{\rm rec}/V_\circ$	e	$P''_f/P_\circ$	f_v
10	0.8	12.93	15.8	5.33	0.022	0.045	14.2	0.045
	0.6	8.18	13.8	6.64	0.027	0.051	9.1	0.050
	0.4	3.86	11.8	9.18	0.036	0.060	4.4	0.060
	0.3	2.13	10.8	11.64	0.046	0.065	2.4	0.065
12	0.8	9.84	18.7	10.20	0.040	0.073	11.4	0.073
	0.6	6.26	16.3	12.70	0.048	0.083	7.4	0.083
	0.4	2.99	13.9	17.55	0.065	0.096	3.7	0.096
	0.3	1.65	10.7	22.25	0.082	0.104	2.0	0.104
25	0.8	3.61	35.9	22.70	0.069	0.098	5.3	0.098
	0.6	2.38	30.9	28.01	0.083	0.114	3.8	0.115
	0.4	1.20	25.9	38.23	0.111	0.135	2.0	0.136
	0.3	0.69	23.4	48.07	0.140	0.148	1.2	0.149
35	0.8	2.39	47.6	38.00	0.112	0.136	4.1	0.137
	0.6	1.62	40.6	46.52	0.139	0.158	2.9	0.160
	0.4	0.85	33.6	62.76	0.201	0.190	1.8	0.193
	0.3	0.50	30.1	78.29	0.250	0.211	1.2	0.213

[a] for $P_o = 5^{\rm d}$

It finally leaves the binary system via the second Lagrangian point L_2, carrying specific angular momentum with it (de Loore & De Greve 1992). The specific angular momentum of this lost matter is considerably larger than what is lost in the specific amount of angular momentum in the stellar wind (given by Eq. 5), see for example Soberman et al. (1997).

We assume that the mass that leaves the system carries a fraction β of the specific angular momentum of the binary. We can then write the change in orbital separation due to mass transfer as

$$\frac{a'}{a_\circ} = \left(\frac{M_f m_f}{M_\circ m_\circ}\right)^{-2} \left(\frac{M_f + m_f}{M_\circ + m_\circ}\right)^{2\beta+1}. \tag{17}$$

and use it as an alternative for Eq. (7). Following Portegies Zwart (1995) we use $\beta = 3$.

Eq. (8) then becomes:

$$\frac{a'}{a_\circ} = \left(\frac{1}{q_\circ p(2-p)}\right)^2 \left(\frac{1+q_\circ}{p+q_\circ(2-p)}\right)^{-2\beta-1} \times \left(1 - \frac{\delta}{1+q_\circ}\right)^{-1} \tag{18}$$

The result of this calculation is presented as the dotted lines in Fig. 1. The small number near each $\circ$ indicates the mass of the visible component, which is smaller than if mass transfer would proceed conservatively. One observes that for the same mass of the visible component of the binary, the runaway velocity of the OB-system is between 50 and 100 per-cent larger than in the conservative case. The higher velocity of the binary is mainly caused by the smaller orbital separation at the moment of the supernova. We thus see, from this simple numerical experiment, that non-conservative mass transfer makes the difference in runaway velocity between the two types of high mass X-ray binaries considerably larger.

5. Predicted and observed orbital eccentricities of the Be/X-ray binaries: evidence for kicks

5.1. Orbital eccentricities of Be/X-ray binaries in case of symmetric ejection

In the case of spherically symmetric mass ejection the orbital eccentricity induced by the mass loss is (cf. Hills 1983):

$$e = \frac{\Delta M_{\rm sn}}{M'_{\rm tot} - \Delta M_{\rm sn}} \equiv \frac{\Delta M_{\rm sn}}{M''_{\rm tot}}. \tag{19}$$

One expects that because of the extensive mass transfer and the fact that before the mass transfer the primary was a (sub)giant, the orbits just prior to the explosions are circular. Hence, in case of spherically symmetric mass ejection, one expects the eccentricities of the Be/X-ray binaries simply to be given by Eq. (19).

Table 3 shows that for the Be/X-ray binaries resulting from systems with an initial primary mass of $10\,{\rm M}_\odot$, the orbital eccentricities expected on the basis of Eq. (19) range from 0.045 to 0.060. For systems resulting from binaries with primaries of $12\,{\rm M}_\odot$, the eccentricities range from 0.073 to 0.096. It should be noted that these are, in fact, overestimates, since we ignored case BB mass transfer, which would still have somewhat reduced these values.

Table 3. Orbital parametres of the seven Be/X-ray binaries with known orbital periods and measured or estimated orbital eccentricities, together with those of the two radio pulsars with B-type companions. Column 5 gives an estimate of the recoil velocity of the binary assuming symmetric mass loss. Columns 6 and 7 indicate the orbital eccentricities which would have been induced by symmetric supernova mass ejection that imparted runaway velocities of 10 and 20 $\mathrm{km\,s^{-1}}$ to the systems, respectively. Column 8 lists the minimum kick velocities, that should have been imparted to their neutron stars to produce their actually observed orbital eccentricities without imparting a runaway velocity larger than 20 $\mathrm{km\,s^{-1}}$ to the systems. References to the orbital parameters of the systems: (1) van Paradijs (1985); (2) Corbet at al. (1986); (3) Priedhorsky & Terrell (1983); (4,5) Parmar et al. (1989a, 1989b); (6) Johnston et al. (1992); (7) Kaspi et al. (1994); (8) Kaspi et al. (1996a); (9) Kaspi et al. (1996b).

System	$P_{\rm orb}$ [days]	e (observed)	$\langle V_{\rm orb}\rangle^{\rm a}$ [$\mathrm{km\,s^{-1}}$]	$V_{\rm rec}{}^{\rm b}$ [$\mathrm{km\,s^{-1}}$]	‘symmetric’ e-expected for $V_{\rm rec}=10$ [$\mathrm{km\,s^{-1}}$]	$V_{\rm rec}=20$ [$\mathrm{km\,s^{-1}}$]	required minimum $V_{\rm kick}$ [$\mathrm{km\,s^{-1}}$]	Ref.
X0115+634	24.3	0.34	60.1	182.8	0.06	0.11	66	(1)
X0331+53	34.3	0.31	53.5	162.7	0.06	0.12	53	(1,3)
X0535+26	111.0	≥ 0.4	42.8	108.4	0.09	0.18	47	(1)
X0535−67	16.7	≥ 0.7	184	207	0.05	0.10	203	(1)
X1145−619	187.5	$\geq 0.7^c$	82.3	92.4	0.11	0.21	90.5	(1)
X1258−613	133	$\geq 0.7^c$	92.7	103.9	0.10	0.19	102.0	(2,3)
EXO2030+375	46	0.38	55.1	147.6	0.07	0.13	60.6	(4,5)
PSRJ1259−63	1236.8	0.87	79.1	49.3	0.20	0.39	87	(6)
PSRJ0045−7319	51.17	0.81	179	142.5	0.07	0.14	195.4	(7,8,9)

[a] As defined by Eq. (20)
[b] From Eq. (22)
[c] Estimated in the text

Orbital eccentricities are known for only five Be/X-ray binaries, as is listed in Table 3. They range from 0.3 to >0.7, with an average of about 0.5. For the two long-period systems, 1145-619 and 1258-613, the orbital eccentricities have not yet been measured, but a rough estimate of their values can be made as follows. Both systems are recurrent transients, with outbursts occurring once per orbit, when the Be star is active, presumably when the stars are near periastron. The same is true for the systems 0115+63, V0331+53 and EX02030+375 when their Be-stars are in an active phase. For the latter systems one calculates from their orbital periods and eccentricities that within 20 percent their periastron distances are the same. Apparently, this is the periastron distance required for triggering an outburst when the Be-star is in an active phase. It thus seems reasonable to assume that the same is true for 1145-619 and 1258-613. Using this, one finds the latter systems to have eccentricities of between 0.75 and 0.83, and between 0.70 and 0.80, respectively. To be conservative, we have indicated this in Table 3 as: $e \geq 0.70$.

Two more systems consisting of a B-star and a neutron star are known: the binary radio pulsars PSRJ 1259-63 and PSRJ 0045-7319. These have very eccentric orbits as indicated in Table 3. So, in total we have nine B-star plus neutron star systems with measured or estimated orbital eccentricities. References to the orbital parameters of these systems are indicated in the table.

Observations show that all binaries –including detached ones– with orbital periods shorter than 10 days have circular orbits, whereas detached systems with longer orbital periods do not. This suggests that in systems with orbital periods shorter than 10 days tidal forces are effective in circularizing the orbits on a timescale considerably shorter than the lifetimes of the components of the binary, whereas in wider systems they apparently are not. Since the Be/X-ray binaries are detached systems (cf. van den Heuvel & Rappaport 1987; van den Heuvel 1994) and have orbital periods longer than 16 days, it is not surprising that their orbits have not yet been circularized.

The lifetime of a Be/X-ray binary is expected to be of the order of a few million years up to about 10 Myr, the lifetime of the Be companion of the neutron star. The timescale for tidal circularization for main-sequence binaries with orbital periods >16 days is at least a few tens of Myr (see Zahn 1977, Kochanek 1992). Therefore it is unlikely to catch the binary in the circularization process. Therefore, we expect that the eccentricities for the Be/X-ray binaries in Table 3 are still close to those just after the supernova explosion. The orbits of the high-mass X-ray binaries with orbital periods <10 days are all practically circularized by tidal effects.

It should be noted that if the eccentricities of the Be-systems had resulted from spherically symmetric supernova mass ejection, the amounts of mass ejected in their supernovae should have been very large, of order 4 to over 7 solar masses (see for example Iben & Tutukov 1998). Since in the case of symmetric mass ejection the orbital eccentricity and runaway velocity are directly proportional to each other (see Eqs. [10] and [14]), also the induced runaway velocities should have been much larger than observed. For example, induction of an eccentricity 0.5 with a symmetric explosion requires 1/3 of the system mass to be ejected in the explosion. With a Be star of 12 $\mathrm{M}_{\odot}$, as is representative for a typical B0.5 Ve star, and a neutron star mass of 1.4 $\mathrm{M}_{\odot}$, the initial system mass in this case must have been 20.1 $\mathrm{M}_{\odot}$, implying an ejected amount of mass of 6.7$\mathrm{M}_{\odot}$. In order to obtain a post-supernova orbital period of about 30 days, as is typical for many Be/X-ray binaries, the initial orbital period in this example must have been around 11 days. With this initial period, and 6.7 $\mathrm{M}_\odot$ explosively ejected, the induced runaway velocity $V_{\rm rec}$ would be $\simeq 87\,\mathrm{km\,s^{-1}}$(see the equations in Sect. 3.2), which is advariant with the observed velocities.

Similarly, if the induced eccentricity would be 0.3, one finds that for the same final system mass and orbital period, the runaway velocity induced by the explosion would have been about $45\,\mathrm{km\,s^{-1}}$.

As these velocities are some 5, respectively 2.5 times larger than the mean excess space velocity of $19\,\mathrm{km\,s^{-1}}$ $[(4/\pi)\times 15\,\mathrm{km\,s^{-1}}]$ of the Be/X-ray binaries, it is clear that the orbital eccentricities of the Be/X-ray binaries cannot be due purely to symmetric mass ejection in the supernova explosion.

The only way to obtain both a low runaway velocity of the system and the high orbital eccentricities listed in Table 3 is by having a small amount of mass ejected in the supernova, in combination with a velocity kick of order 60 to 250 $\mathrm{km\,s^{-1}}$ imparted to the neutron star at birth. We describe below how these required kick velocities were calculated. The randomly directed kick hardly changes the runaway velocity of the system, as the impulse of the kick imparted to the neutron star is shared by the entire system (with a mass of order 15 solar masses in the case of the Be/X-ray binaries), and thus the kick velocity is "diluted" to an extra velocity of the system of only 4 to 16 $\mathrm{km\,s^{-1}}$, in a random direction. Adding this velocity quadratically (because of its random direction) to the velocity of between 5 and 21 $\mathrm{km\,s^{-1}}$ imparted to the systems purely by the mass loss (Fig. 1), one obtains mean runaway velocities of between 6 and 21 $\mathrm{km\,s^{-1}}$ for a 60 $\mathrm{km\,s^{-1}}$ kick and between 17 and 26 $\mathrm{km\,s^{-1}}$ for a 250 $\mathrm{km\,s^{-1}}$ kick.

These values are in good agreement with the observed mean excess space velocities of Be/X-ray binaries of $19\pm 8\,\mathrm{km\,s^{-1}}$($\pi/4$ times their average peculiar tangential velocities).

We calculated the minimum kick velocities that have to be imparted to the neutron star during the supernova explosion in order to obtain the presently observed orbital eccentricities of the Be-systems in Table 3. We used the equations derived by Wijers et al. (1992). The minimum required kick velocitiy is the one that is imparted in the orbital plane in the direction of motion of the pre-supernova star (assuming the initial orbit was circular). We assumed in these calculations that the B stars have a mass of $15\,\mathrm{M}_\odot$, as corresponds to a B0-1 main-sequence star, and that the neutron star has a mass of $1.4\,\mathrm{M}_\odot$. (For B-star masses in the range $10-20\,\mathrm{M}_\odot$ the required minimum runaway velocities do not differ by more than $\pm$ 10 per cent from the values for $15\mathrm{M}_\odot$). The table shows that the required minimum kick velocities range from about 50 $\mathrm{km\,s^{-1}}$ to about 200 $\mathrm{km\,s^{-1}}$. Assuming the real kick velocities to be randomly distributed, the required kicks become $\sqrt{3/2}$ times larger, and range from about 60 to about 250 $\mathrm{km\,s^{-1}}$.

We conclude from the above that the combination of low mean space velocity of the Be/X-ray binaries and large mean orbital eccentricity provides unequivocal evidence for the existence of velocity kicks imparted to neutron stars at their birth.

An alternative way to approach the problem of the orbital eccentricities is to calculate, from the measured mean runaway velocities of Be/X-ray systems, what orbital eccentricity these systems should have had, were this runaway velocity imparted by purely symmetric mass ejection. This is the topic of the next section.

5.2. Predicted relation between orbital eccentricity and runaway velocity expected in case of symmetric explosions – comparison with observations

Eq. (11) yields:

$$\frac{e}{1+e}=\frac{\Delta M_{\rm sn}}{M'_{\rm tot}}, \tag{20}$$

Combination of Eqs. (10) and (20) yields:

$$V_{\rm rec}=\sqrt{\frac{GM''_{\rm tot}}{a'}}\frac{m_f}{M''_{\rm tot}}\frac{e}{1+e}, \tag{21}$$

where a' is the pre-supernova orbital radius. The semi-major axis after the supernova a'' follows from:

$$\frac{a'}{a''}=1-\frac{\Delta M_{\rm sn}}{M''_{\rm tot}}, \tag{22}$$

and by writing

$$M'_{\rm tot}=M''_{\rm tot}+\Delta M_{\rm sn}=M''_{\rm tot}(1+\frac{\Delta M_{\rm sn}}{M''_{\rm tot}}). \tag{23}$$

One obtains after insertion of Eq. (8) in Eq. (13):

$${V_{\rm rec}}^2=\frac{GM''_{\rm tot}}{a''}\frac{1+\Delta M_{\rm sn}/M''_{\rm tot}}{1-\Delta M_{\rm sn}/M''_{\rm tot}}\left(\frac{m_f}{M''_{\rm tot}}\right)^2\left(\frac{e}{1+e}\right)^2. \tag{24}$$

Defining now the presently observed mean orbital velocity by

$$\langle V_{\rm orb}\rangle^2=\frac{GM''_{\rm tot}}{a''}, \tag{25}$$

and substituting $\Delta M_{\rm sn}/M''_{\rm tot}$ from Eq. (19) one obtains:

$$\frac{V_{\rm rec}}{\langle V_{\rm orb}\rangle}\frac{M''_{\rm tot}}{m_f}=\frac{e}{(1-e^2)^{1/2}}. \tag{26}$$

This defines, in the case of symmetric supernova-mass ejection the relation that is expected to be found between the observed system runaway velocity $V_{\rm rec}$ and the observed orbital eccentricity e, for a system with a Be/X-ray star of mass m_f, and observed mean orbital velocity $\langle V_{\rm orb}\rangle$. Since $M''_{\rm tot}=m_f+1.4\,\mathrm{M}_\odot$, and since in general $m_f>10\,\mathrm{M}_\odot$, the quantity $M''_{\rm tot}/m_f$ is close to unity. Defining:

$$f_v\equiv\frac{V_{\rm rec}}{V_{\rm orb}}\frac{M''_{\rm tot}}{m_f}=\frac{e}{(1-e^2)^{1/2}}, \tag{27}$$

one obtains a simple relation between f_v and e, the plotted curve in Fig. 2. In the case of symmetric supernova mass ejection, the

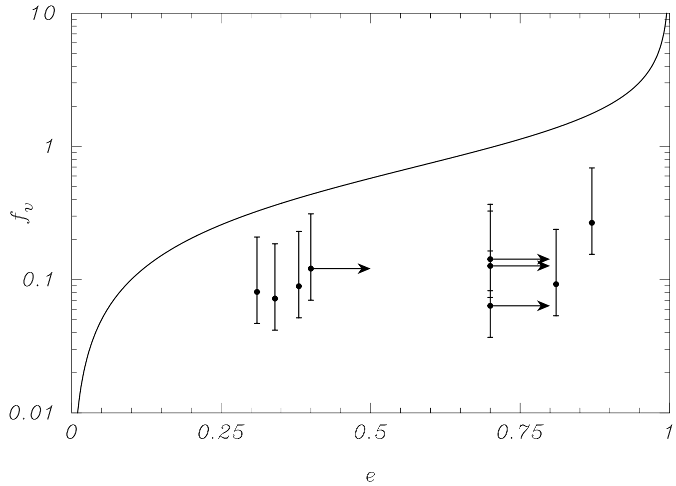

Fig. 2. The system velocity of the runaway binary as a function of the orbital eccentricity induced upon the symmetric explosion of the core of the primary star. Along the vertical axis is the expression: $f_v \equiv V_{\rm rec}/V_{\rm orb} \times M''_{\rm tot}/m_f$ (which is a dimension-less quantity). The observed positions of the nine Be/neutron star systems in this diagram show that the explosions cannot have been symmetric.

observed value of f_v of a Be/X-ray binary should be related to the observed orbital eccentricity according to this curve, which shows that large eccentricities correspond to large runaway velocities.

In Fig. 2 we also plotted the values of f_v and e for the nine systems with observed orbital periods and eccentricities (see Table 3), taking runaway velocities $V_{\rm rec}$ in the observed range $19 \pm 8\ {\rm km\ s^{-1}}$ for the Be X-ray binaries. We assumed a Be-star mass of $15 {\rm M}_\odot$. The figure shows that all systems fall far below the curve expected for symmetric supernova mass ejection. This again shows that the combination of low runaway velocities and large orbital eccentricities as observed in the Be/X-ray binaries cannot be obtained by symmetric mass ejection in the supernovae, and that a velocity kick imparted to the neutron stars at birth is absolutely required.

6. Conclusions

The measured tangential velocities of the Be/X-ray binaries and OB-supergiant X-ray binaries by the *Hipparcos* satellite confirm the expectations from the evolution of massive close binaries in which little mass is lost from the binary systems during the first mass transfer phase. The much higher tangential velocities of supergiant X-ray binaries than those of the Be-systems follow from a combination of (1) the much larger fractional helium core masses in the progenitors of the OB-supergiant systems which cause their pre-supernova orbital periods to be shorter, and thus their pre-supernova orbital velocities to be much larger than those of the less massive Be-systems, and (2) the much lower amounts of mass ejected during the supernova explosion in the lower-mass Be-systems compared to the OB-supergiant systems.

The combination of a high orbital eccentricity with a low space velocity observed for the Be type X-ray binaries can only be understood if a kick with appreciable velocity –in the range 60 to 250 ${\rm km\ s^{-1}}$– is imparted to the newly born neutron star. Such a kick tends to only slightly affect the space velocity of the binary system since the neutron star has to drag along its massive companion. The orbital eccentricity, however, is strongly affected by such a asymmetric velocity kick. If the supernova explosions in these systems had been symmetric, the high orbital eccentricities observed in the class of Be X-ray binaries are impossible to reconcile with their on average low runaway velocities.

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