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Tidal interaction in High-Mass X-ray Binaries

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Our aim is to investigate tidal interaction in High-Mass X-ray Binary stars in order to determine in which objects the rotation of the mass donors is synchronized or pseudosynchronized with the orbital motion of the compact companion. We calculate the pseudosynchronization period ($P_{\rm ps}$) and compare it with the rotational period of the mass donors ($P_{\rm rot}$). We find that (1) the Be/X-ray binaries are not synchronized, the mass donors rotate faster than the orbital period and the ratio $P_{\rm ps}/P_{\rm rot}$ is 2–300; (2) the giant and supergiant systems are close to synchronization and for them the ratio $P_{\rm ps}/P_{\rm rot}$ is 0.3–2.

1 Introduction

The High-Mass X-ray Binaries (HMXRBs) contain a primary star of spectral type O or B and a compact object (neutron star or black hole) as a companion. The mass donors have a mass greater then 10 $M_\odot$. They are Population I objects and are concentrated in the Galactic plane. In the majority of HMXRBs the neutron star is detected as an X-ray pulsar. They are separated in two groups: (1) High-Mass Supergiant and Giant Systems, where the mass donor is an O–B giant or supergiant. Accretion is realized by Roche lobe overflow or via a stellar wind or a combination of both. (2) Be/X-ray binaries, where the mass donor is a main sequence Be star. The compact object accretes mainly from the dense circumstellar disk around the Be star, although the accretion from a polar wind also has some contribution.

The last edition of the catalogue of the galactic HMXRBs contains 114 objects (Liu, van Paradijs & van den Heuvel 2006). Among the 68 objects with identified primaries $\sim$60% are Be/X-ray binaries, $\sim$15% are classified as giants, and $\sim$22% are supergiant/X-ray binaries. The catalogue of HMXRBs in the Magellanic Clouds contains 128 binaries (Liu, van Paradijs & van den Heuvel 2005), where most of the objects (76%) are known or suspected Be/X-ray binaries.

As a result of the accretion of matter from the OB primary, the compact object in these binaries is a strong X-ray emitter and displays different types of activity (cf. Campana et al. 1995; Okazaki & Negueruela 2001; Ducci et al. 2008 and references therein). The rotation of the neutron stars in HMXRBs has been investigated in detail with the X-ray satellites (see Bildsten et al. 1997) and their spin period is connected with the orbital period (Corbet 1984).

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Our aim here is to check whether the rotation of the mass donors in HMXRBs is synchronized with the orbital motion of the compact object, and how the presence of an orbiting neutron star and the tidal force influences the rotation of the mass donor.

2 Synchronization and pseudosynchronization

2.1 Rotation and pseudosynchronization

In a binary with a circular orbit the rotational period of the primary, $P_{\rm rot}$, reaches an equilibrium value at the orbital period, $P_{\rm orb} = P_{\rm rot}$. In other words the synchronous rotation (synchronization) means that the rotational period is equal to the orbital period. In a binary with an eccentric orbit, the corresponding equilibrium is reached at a value of $P_{\rm rot}$ which is *less* than $P_{\rm orb}$, the amount less being a function solely of the orbital eccentricity e. In practice, in a binary with an eccentric orbit the tidal force acts to synchronize the rotation of the mass donor with the motion of the compact object at the periastron-pseudosynchronous rotation (Hall 1986). To calculate the period of pseudosynchronization, $P_{\rm ps}$, we use (Hut 1981)

$$P_{\rm ps} = \frac{(1+3e^2+\frac{3}{8}e^4)(1-e^2)^{\frac{3}{2}}}{1+\frac{15}{2}e^2+\frac{45}{8}e^4+\frac{5}{16}e^6} P_{\rm orb}\,. \quad (1)$$

At low eccentricity of the orbit, $e \to 0$ and $P_{\rm ps} \approx P_{\rm orb}$.

To calculate $P_{\rm rot}$ we use

$$P_{\rm rot} = \frac{2\pi R_1 \sin i}{v \sin i}, \quad (2)$$

where $v \sin i$ is the projected rotational velocity of the mass donor, and i is the inclination of the orbit to the line of sight. The underlying assumption is that the rotational axis of the mass donor is perpendicular to the orbital plane.

2.2 Rotation of the mass donors in HMXRBs

We searched in Liu, van Paradijs & van den Heuvel (2000) and in the literature and find 13 HMXRBs with well measured orbital and stellar parameters. The data are collected in Tables 1 and 2. These are objects for which we were able to find the spectral type of the mass donor, orbital period, eccentricity of the orbit, inclination (i), and projected rotational velocity of the primary ($v \sin i$). The sources of data for each object are given in Sect. 3.

Using Eqs. (1) and (2) and the data collected in Table 1, we calculated $P_{\rm ps}$ and $P_{\rm rot}$ for the objects in our sample. The values are given in Table 1.

In Fig. 1 we plot $P_{\rm rot}$ versus $P_{\rm ps}$. In this figure it is seen that the objects where the mass donors are from spectral class I are located close to the line $P_{\rm ps} = P_{\rm rot}$ (synchronization/pseudosynchronization), while those with mass donors from spectral class V are far away from the equilibrium state.

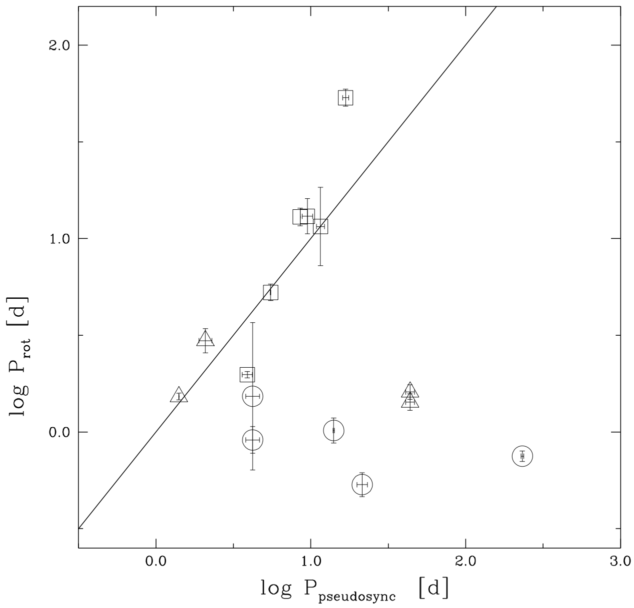

Fig. 1 $P_{\rm rot}$ versus $P_{\rm ps}$ on a logarithmic scale. The straight line indicates $P_{\rm ps} = P_{\rm rot}$. The circles indicate the Be/X-ray binaries (luminosity class V), the triangles those with giant primaries (luminosity class III), the squares supergiants (luminosity class I). For the systems LSI+61°303 and V725 Tau we found two values for $v \sin i$, so there are two points for each of them.

2.3 Circularization and synchronization time scales

Following Hurley, Tout & Pols (2002) and Zahn (1975) the circularization timescale for stars with radiative envelopes can be estimated as

$$\frac{1}{\tau_{\rm circ}} = \frac{21}{2}\left(\frac{GM_1}{R_1^3}\right)^{\frac{1}{2}} q_2\,(1+q_2)^{\frac{11}{6}}\,E_2\left(\frac{R_1}{a}\right)^{\frac{21}{2}}, \quad (3)$$

where M_1 and R_1 are the mass and the radius of the primary respectively, q_2 is the mass ratio M_2/M_1, and a is the semi-major axis. E_2 is a second-order tidal coefficient,

$$E_2 = 1.592\times10^{-9} M_1^{2.84}. \quad (4)$$

The synchronization time scale (Hurley et al. 2002) is given as

$$\tau_{\rm sync} = K\tau_{\rm circ}, \quad (5)$$

where K is

$$K \approx \frac{0.015}{r_{\rm g}}\,\frac{1+q_2}{q_2}\left(\frac{R_1}{a}\right)^2. \quad (6)$$

For the gyration radius of the primary $r_{\rm g}^2 = I/M_1R_1^2$ (where I is the moment of inertia), we adopt $r_{\rm g} \approx 0.16$ for giants, and $r_{\rm g} \approx 0.25$ for main sequence stars (Claret & Gimenez 1989).

In Table 2 are given the adopted stellar parameters, and the calculated $\tau_{\rm circ}$ and $\tau_{\rm sync}$.

2.4 Lifetimes

The lifetime of a star on the main sequence can be estimated as (Germany et al. 2009)

$$\tau_{\rm MS} = 10^{10}\left(\frac{M_\odot}{M}\right)^{2.5}\ \ {\rm yr}. \quad (7)$$

For example, a B0V star with a mass $\sim$20 M$_\odot$ spends $\sim$5.5 $\times10^6$ yr on the main sequence. Comparing these lifetimes with $\tau_{\rm sync}$ from Table 2, we see that among the Be/X-ray binaries only for LSI+61°303 is $\tau_{\rm sync} \sim \tau_{\rm MS}$. This is the only Be/X-ray binary for which we can expect considerable changes of the rotation of the primary during the lifetime of the Be star.

In comparison, the lifetime of a giant of $\sim$20 M$_\odot$ is about $0.1\tau_{\rm MS}$ ($\sim5\times10^5$ yr). The calculated lifetimes are given in Table 2. The lifetime of the giant is comparable or longer then $\tau_{\rm circ}$ and $\tau_{\rm sync}$ (see Table 2) for the giant/supergiant systems with short orbital periods ($P_{\rm orb}$ < 20 d). The exceptions are V725 Tau and BP Cru, for which $\tau_{\rm sync}$ and $\tau_{\rm circ}$ are longer than the lifetime of the giant/supergiant stage.

For the giant/supergiant systems, we ignore the preceding evolution, because (1) during the main-sequence stage the tidal interaction is considerably weaker, and (2) changes of the orbit at the supernova explosion.

3 Individual objects

3.1 Be/X-ray binaries

LSI+61°303 (V615 Cas, GT0236+610): The system contains a compact object (probably a black hole) orbiting around a Be star in a highly eccentric orbit (Hutchings & Crampton 1981; Casares et al. 2005). The parameters of the system are not well defined. We calculate $P_{\rm ps}/P_{\rm rot} \approx 2\pm1$. LSI+61°303 is the closest to pseudosynchronization among the Be/X-ray binaries in our sample.

Table 1 Orbital parameters of HMXRB stars. Given here are as follows: name of the object, orbital period, eccentricity of the orbit, inclination of the orbit to the line of sight, semi-major axis of the orbit, projected rotational velocity ($v \sin i$) of the mass donor, the period of pseudosynchronization (calculated using Eq. (1)), rotational period of the mass donor (calculated using Eq. (2)).

Object	$P_{\rm orb}$ [d]	e	i [°]	a [$R_\odot$]	$v \sin i$ [$\rm km\,s^{-1}$]	$P_{\rm ps}$ [d]	$P_{\rm rot}$ [d]
Be/X-ray binaries							
LSI+61°303	26.496	0.72±15	30±20	35.45	113	1.10–7.33	0.45–2.61
			70–80		360		0.77–1.05
X Per	250±0.6	0.111±0.018	26–33	474	215±10	228–237	0.70–0.80
BQ Cam	34.25	0.31±0.03	≤10.3±0.09	121	145	19.82–23.11	0.46–0.61
V635 Cas	24.3	0.34	40–60	95	300	14.06	0.87–1.17
Giant systems							
V725 Tau	111	0.47±0.02	28.5	23.39	254	40.93–46.62	1.43
					225		1.61
LMC X-4	1.4084	0.006(2)	25–29	13.3	240±25	1.4079–1.4083	1.46–1.59
Cen X-3	2.0871	0.0016	70.2±2.7	17.9	200±40	2.09	2.54–3.39
Supergiant systems							
V830 Cen	14.365±0.002	0.20±0.03	40–55	58.6	150	10.87–12.23	6.51–16.58
LSI+65°010	11.5983	0.18±0.05	45	56	96±20	8.78–10.25	10.36–15.74
Vela X-1	8.9644	0.0898±0.0012	76^{+5}_{-9}	50.1	116±6	8.54–8.56	11.59–14.29
SMC X-1	3.89229	$<4\times10^{-5}$	26–30.5	25	170±30	3.89	1.90–2.06
BP Cru	41.498±0.002	0.462±0.014	60±10	182	50	16.03–17.54	48.08–58.98
Cyg X-1	5.5	0.06±0.01	33±5	15.48	100	5.48–5.52	4.75–5.79

X Per (4U 0352+30): The stellar parameters are taken from Roche et al. (1997), Delgado-Martí et al. (2001) and Lyubimkov et al. (1997). The system is non-synchronized with $P_{\rm ps}/P_{\rm rot} \approx 310\pm15$. The tidal force should spin down the rotation of the mass donor, however it is very weak ($\tau_{\rm sync} \sim 10^{17}$ yr), so there should be no changes during the lifetime as a Be/X-ray binary. It has persistent X-ray emission because the neutron star accretes from the outer parts of the stellar wind, where there are no changes in the density of the material.

BQ Cam (V0332+53): We calculate a ratio $P_{\rm ps}/P_{\rm rot} \approx 40\pm3$. The tidal force spins down the rotation of the mass donor. The stellar parameters are taken from Negueruela et al. (1999). The lack of recent X-ray activity is explained by the fact that the dense regions of the circumstellar disc around the Oe star do not reach the orbit of the neutron star.

V635 Cas (4U0115+63): This system is a transient X-ray emitter. We took the stellar parameters from Negueruela et al. (2001). The ratio $P_{\rm ps}/P_{\rm rot} \approx 14\pm2$ shows that the tidal force is spinning down the rotation of the mass donor. The disc around the Be star was modeled as a viscous decretion disc, i.e., a quasi-Keplerian disc held by the transport of angular momentum via viscous interactions. The outflow (radial) velocity in such a disc is expected to be strongly subsonic, in agreement with all the observations of Be stars in general and V635 Cas in particular. It was shown that such a disc cannot reach a steady state due to tidal and resonant interaction with the neutron star, and it is truncated at a radial distance which depends on the value of the viscosity (Negueruela & Okazaki 2001; Reig et al. 2007).

3.2 Systems containing a giant donor

V725 Tau (1A 0535+262): The stellar parameters are taken from Clark et al. (1998), Haigh, Coe & Fabregat (2004), and Grundstrom et al. (2007a). $P_{\rm ps}/P_{\rm rot} \approx 30\pm2$. The tidal force spins down the rotation of the mass donor. The X-ray source A0535+262 was discovered by Ariel V during a large Type II outburst in 1975 (Coe et al. 1975; Rosenberg et al. 1975). Since then the source has been observed to undergo numerous outbursts, however there were no reported detections of X-ray outburst activity from 1994 to 2005 (Coe et al. 2006; Kretschmar et al. 2006). The source reappeared in a Type II outburst in May/June 2005 and was detected by Swift (Tueller et al. 2005) and RHESSI (Smith et al. 2005). It was subsequently seen to undergo a Type I outburst in August 2005 (Kretschmar et al. 2006; Caballero et al. 2007).

In respect to its X-ray behaviour and rotation of the mass donor (and ratio $P_{\rm ps}/P_{\rm rot}$) this object is similar to the transient Be/X-ray binaries.

LMC X-4: Kelley et al. (1983) discovered the 13.5 s X-ray pulsations of LMC X-4. The optical light curve shows ellipsoidal variations and a super-orbital period of ∼30 d (Heemskerk & van Paradijs 1989). The X-ray light curve includes regular eclipses as well as a pronounced flux modulation of a factor ∼60 with a period of 30.5 d (Lang et al. 1981). This long-term variation is attributed to the precessing accretion disc. The stellar parameters are taken from van der Meer et al. (2007). $P_{\rm ps}/P_{\rm rot} \approx 0.92\pm0.04$. The rotation of the mass donor is synchronized with the orbital motion. In this respect it is similar to the supergiant systems.

Table 2 HMXRB star parameters of the components. Given here are the name of the object, the spectral type of the primary, mass of the primary, mass of the secondary, radius of the primary, its luminosity, synchronization time scale, circularization time scale, the lifetime, the action of the tidal force.

Object	Sp. Type	M_1 [$M_\odot$]	M_2 [$M_\odot$]	R_1 [$R_\odot$]	L_1 [$L_\odot$]	$\tau_{\rm sync}$ [yr]	$\tau_{\rm circ}$ [yr]	Lifetime [yr]	Tidal Force
Be/X-ray binaries									
LSI+61°303	B0 Ve	20.0	4.0	6.7±0.9	3×10^3	3.1×10^6	6.8×10^7	5.6×10^6	Pseudosync./spin-down
X Per	B0 V	15.5	1.4	6.5	3×10^3	6.2×10^{17}	1.8×10^{21}	1.1×10^7	Spin-down
BQ Cam	O8–9 Ve	23.0	1.4	9.0	5.5×10^3	3.5×10^{11}	7.6×10^{13}	3.9×10^6	Spin-down
V635 Cas	B0.2 Ve	18.0	1.4	8.0	3×10^3	1.4×10^{11}	9.5×10^{12}	7.3×10^6	Spin-down
Giant systems									
V725 Tau	O9.4 IIIe	23.0	1.4	15.0	2.0×10^5	2.8×10^{12}	8.0×10^{14}	4×10^5	Spin-down
LMC X-4	O8 III	15.8	1.47	7.8±0.3	2.0×10^5	4.5×10^2	7.7×10^2	1×10^6	Sync.
Cen X-3	O6.5 II–IIIae	20.5	1.4	12.1±0.5	5.0×10^5	2.3×10^3	4.2×10^3	5×10^5	Sync.
Supergiant systems									
V830 Cen	B2 Iae	16.0	1.4	30–60	2.5×10^5	7.5×10^3	1.4×10^4	1×10^6	Pseudosync.
LSI+65°010	B1 Iae	16±5	1.7	37±15	2.5×10^5	1.3×10^4	3.9×10^4	1×10^6	Pseudosync./spin-up
Vela X-1	B0 Ia	23.1	1.9	30.4±1.6	2.5×10^5	1.0×10^4	2.8×10^4	3.9×10^5	Sync./spin-up
SMC X-1	B0 Ib	16.7	1.05	14±2	2.5×10^5	3.3×10^4	8.2×10^4	8.8×10^5	Spin-down
BP Cru	B1.2 Ia	43.0	1.9	62.0	5×10^5	1.8×10^6	8.8×10^6	8×10^4	Spin-up
Cyg X-1	B0 Iab	40±10	20±5	20–22	$3–4\times10^5$	<1	<1	1×10^5	Sync.

Cen X-3 (V779 Cen): The stellar parameters are taken from Ash et al. (1999) and van der Meer et al. (2007). We calculate $P_{\rm ps}/P_{\rm rot} \approx 0.72 \pm 0.1$. The system is close to equilibrium. The optical light curve indicates the likely presence of an accretion disc, but no strong evidence is found for X-ray heating (Tjemkes, van Paradijs & Zuiderwijk 1986). The X-ray light curve includes episodes of high and low X-ray flux with a characteristic timescale of 120–165 d (Priedhorsky & Terrell 1983; Paul, Raichur & Mukherjee 2005). It could be a beating period between $P_{\rm orb}$ and $P_{\rm rot}$, however to prove this we need a higher (better than 1%) accuracy in the measurement of $P_{\rm rot}$.

3.3 Supergiant systems

V830 Cen (1E 1145.1-6141): The pulsar appears to be persistent and steady, with a typical X-ray flux of a few mCrab, corresponding to a luminosity of about 10^{36} erg s^{-1}. Such a low luminosity is inconsistent with Roche lobe overflow and indicates that the pulsar is almost certainly accreting from the wind of V830 Cen. The stellar parameters are taken from Ray & Chakrabarty (2002). $P_{\rm ps}/P_{\rm rot} \approx 1.12 \pm 0.15$. The rotation of the mass donor is pseudosynchronized, the orbit is in a process of circularization.

LSI+65°010 (V662 Cas, 2S 0114+650): The stellar parameters are taken from Grundstrom (2007b). $P_{\rm ps}/P_{\rm rot} \approx 0.75 \pm 0.1$. The neutron star spins up the rotation of the mass donor, and the mass donor is close to pseudosynchronization. No significant X-ray variations are detected in this system.

Vela X-1 (GP Vel): $P_{\rm ps}/P_{\rm rot} \approx 0.67 \pm 0.10$. The stellar parameters are from Zuiderwijk (1995) and Bildsten et al. (1997). It is the brightest persistent accretion powered pulsar. The system is close to equilibrium, but the compact object still spins up the rotation of the mass donor.

SMC X-1 (Sk 160): $P_{\rm ps}/P_{\rm rot} \approx 1.97 \pm 0.07$. The stellar parameters are taken from van der Meer et al. (2007). SMC X-1 demonstrates an orbital variation of 3.89 days and a superorbital variation with an average length of ~55 days (Trowbridge, Nowak & Wilms 2007). The compact object spins down the rotation of the mass donor.

BP Cru (Wray 977): The X-ray binary system GX301-2 consists of a neutron star in an eccentric orbit accreting from the massive early-type star Wray 977. The system parameters are from Kaper, van der Meer & Najarro (2006). We calculate $P_{\rm ps}/P_{\rm rot} \approx 0.31 \pm 0.03$. The system is not synchronized nor circularized. The tidal force spins up the rotation of the mass donor. It has previously been shown that the X-ray orbital light curve is consistent with the existence of a gas stream flowing out from WRAY 977 in addition to its strong stellar wind (Leahy & Kostka 2008). The stream is (should be) a result of the tidal force.

Cyg X-1 (V1357 Cyg): With the stellar parameters given in Ziółkowski (2005) and Iorio (2008), we calculate $P_{\rm ps}/P_{\rm rot} \approx 1.04 \pm 0.11$ The system is the brightest persistent source of hard X-rays. The Cyg X-1 system is synchronized and should be circularized, following the circularization time in Table 2. It is probable that, the measured orbital eccentricity ($e = 0.06$) is a spurious effect of the tidal distortion.

4 Discussion

Our goal is to understand, whether the rotation of the mass donors in HMXRBs is influenced by the orbiting companion (neutron star or stellar mass black hole).

Be/X-ray binaries: In the Be/X-ray binaries the compact object accretes material from the Be star envelope. The circumstellar disks around the Be stars in Be/X-ray binaries are axisymmetric and rotationally supported like the disks in the isolated Be stars; however they are smaller and denser (Zamanov et al. 2001). It seems that transient behaviour in the Be/X-ray binaries is observed when the neutron star is located at a distance from the Be star of $15 < r/R_{\odot} < 450$. In the Be/X-ray binaries BQ Cam, V635 Cas, and V725 Tau, the transient behaviour can be connected with the tidal force spinning down the Be star. Excluding the peculiar object LSI+61°303, for these objects typically $P_{\rm ps}/P_{\rm rot} > 10$.

For the galactic microquasar LSI+61°303 the rotation of the mass donor is close to pseudosynchronization. The system is known to have been ejected from the cluster IC 1805 about 1.5 Myr ago (Mirabel, Rodriguez & Liu 2004). This is the only Be/X-ray binary in which $\tau_{\rm sync}$ is comparable with the life-time of the binary.

In the long period binary X Per the neutron star is far away from the Be star and the tidal force is weak.

Giant and supergiant systems: The systems with a giant or supergiant as the mass donor are persistent X-ray sources and they are close to synchronization/pseudosynchronization, $P_{\rm ps}/P_{\rm rot} \sim 1$. This fact indicates that in these binaries the rotation of the mass donors is influenced by the presence of the compact object.

In LMC X-4 and Cen X-3, the mass donors (giants) are synchronized and the orbits are circularized. With respect to the rotation of the mass donor, V725 Tau is similar to the Be/X-ray binaries.

Cyg X-1 is synchronized and almost circularized. V830 Cen is pseudosynchronized but not circularized yet. The systems LSI+65°010 and Vela X-1 are close to pseudosynchronization and the tidal force accelerates the rotation of the mass donors. From the calculated $\tau_{\rm sync}$ we can estimate their ages (the time the neutron star was born), for LSI+65°010 $\lesssim 3.9\times10^4$ yr, and for V830 Cen $\lesssim 1.4\times10^4$ yr. In the case of SMC X-1, the tidal force acts as a decelerator of the rotation of the mass donor. In BP Cru, a gas stream from the mass donor exists, probably resulting from the strong tidal force and spin-up of the mass donor.

5 Conclusions

In this note we investigate synchronization and pseudosynchronization in the High-Mass X-ray Binary stars. For 13 systems with known orbital and stellar parameters, we calculate the synchronization and circularization timescales, the pseudosynchronization period and compare them with the data for the rotation of the mass donors.

We find that the Be/X-ray binaries are far away from synchronization/pseudosynchronization. For most of them $P_{\rm rot} \ll P_{\rm ps}$. The tidal force in the Be/X-ray binaries acts as a decelerator of the rotation of the mass donors. The only Be/X-ray binary which is close to pseudosynchronization is the peculiar object LSI+61^0303.

The objects containing mass donors of spectral class I (supergiants) and III (giants) typically have $P_{\rm rot} \sim P_{\rm ps}$ and are therefore close to synchronization/pseudosynchronization.

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