Rotation of the Mass Donors in High-mass X-ray Binaries and Symbiotic Stars

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Abstract

Our aim is to investigate the tidal interaction in High-mass X-ray Binaries and Symbiotic 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 find that the Be/X-ray binaries are not synchronized and the orbital periods of the systems are greater than the rotational periods of the mass donors. The giant and supergiant High-mass X-ray binaries and symbiotic stars are close to synchronization. We compare the rotation of mass donors in symbiotics with the projected rotational velocities of field giants and find that the M giants in S-type symbiotics rotate on average 1.5 times faster than the field M giants. We find that the projected rotational velocity of the red giant in symbiotic star MWC 560 is $v \sin i = 8.2 \pm 1.5 \text{ km s}^{-1}$, and estimate its rotational period to be $P_{\text{rot}} = 144$ - 306 days. Using the theoretical predictions of tidal interaction and pseudosynchronization, we estimate the orbital eccentricity $e = 0.68 - 0.82$.

Keywords: stars: binaries: symbiotic - stars: rotation - stars: late type - stars: binaries: close - X-rays: binaries.

1 Introduction

A High-mass X-ray binary system consists of a compact object (a neutron star or a black hole) accreting material from an O or B companion star. They are divided into Be/X-ray binaries (main-sequence star as a companion) and Giant/Supergiant X-ray binaries (giant or supergiant star as a companion). Accretion of matter is different for both types of X-ray binaries. In the Be/X-ray binaries, the compact object crosses the circumstellar disc and accretes matter from that disk. In the giant/supergiant X-ray binaries, the mass donor ejects a slow and dense wind radially outflowing from the equator and the compact object directly accretes the stellar wind through Bondi-Hoyle-Lyttleton accretion.

Symbiotic stars are interacting binaries, consisting of an evolved giant (either a normal red giant in S-types symbiotics or a Mira-type variable in D-types symbiotics) transferring mass to a hot and luminous white dwarf or neutron star. The symbiotic stars are surrounded by a rich and luminous nebula resulting from the presence of both an evolved giant with a heavy mass-loss and of a hot companion abundant in ionizing photons and often emanating its own wind.

2 Synchronization and Pseudosynchronization

In a binary with a circular orbit the rotational period of the primary, P_{rot}, reaches an equilibrium value at the orbital period, $P_{orb} = P_{rot}$. 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_{rot} which is less than P_{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. To calculate the period of pseudosynchronization, P_{ps}, we use (Hut 1981):

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

2.1 Stars with radiative envelopes

Following Hurley, Tout & Pols (2002) the circularization timescale for stars with radiative envelopes is:

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

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. The second-order tidal coefficient $E_2 = 1.592 \times 10^{-9} M_1^{2.84}$.

The synchronization time scale is given as,

$$\tau_{sync} = K\tau_{circ}, \tag{3}$$

where K is:

$$K \approx \frac{0.015}{r_g} \frac{1+q_2}{q_2} \left(\frac{R_1}{a}\right)^2. \tag{4}$$

For the gyration radius of the primary r_g we adopt $r_g \approx 0.16$ for giants, and $r_g \approx 0.25$ for main sequence stars (Claret & Gimenez, 1989).

2.2 Stars with convective envelopes

Following Hurley, Tout & Pols (2002) the synchronization timescale for stars with convective envelopes is:

$$\tau_{\mathrm{syn}} \approx 800 \left(\frac{M_1 R_1}{L_1}\right)^{1/3} \frac{M_1^2 (\frac{M_1}{M_2} + 1)^2}{R_1^6} P_{\mathrm{orb}}^4 \ \ \mathrm{yr}, \tag{5}$$

where L_1 is the luminosity of the giant.

The circularization time scale is:

$$\frac{1}{\tau_{\mathrm{circ}}} = \frac{21}{2} \left(\frac{k}{T}\right) q_2(1+q_2) \left(\frac{R_1}{a}\right)^8. \tag{6}$$

In Eq. 6, (k/T) is:

$$\left(\frac{k}{T}\right) = \frac{2}{21} \frac{f_{\mathrm{conv}}}{\tau_{\mathrm{conv}}} \frac{M_{\mathrm{env}}}{M_1} \ \mathrm{yr}^{-1}, \tag{7}$$

where R_{env} is the depth of the convective envelope, M_{env} is the envelope's mass, and

$$\tau_{\mathrm{conv}} = 0.4311 \left(\frac{M_{\mathrm{env}} R_{\mathrm{env}} (R_1 - \frac{1}{2} R_{\mathrm{env}})}{3L_1}\right)^{\frac{1}{3}} \mathrm{yr} \tag{8}$$

is the eddy turnover time scale (the time scale on which the largest convective cells turnover). The numerical factor f_{conv} is

$$f_{\mathrm{conv}} = \min \left[1, \left(\frac{P_{\mathrm{tid}}}{2\tau_{\mathrm{conv}}}\right)^2\right], \tag{9}$$

where P_{tid} is the tidal pumping time scale given by

$$\frac{1}{P_{\mathrm{tid}}} = \left|\frac{1}{P_{\mathrm{orb}}} - \frac{1}{P_{\mathrm{rot}}}\right|. \tag{10}$$

The pseudosynchronization timescale is $\tau_{\mathrm{ps}} = (7/3(\alpha - 3)) \tau_{\mathrm{circ}}$, where α is a dimensionless quantity, representing the ratio of the orbital and rotational angular momentum:

$$\alpha = \frac{q_2}{1+q_2} \frac{1}{r_{\mathrm{g}}^2} \left(\frac{a}{R_1}\right)^2. \tag{11}$$

For a red giant we adopt $r_{\mathrm{g}} \approx 0.3$ (Claret, 2007).

In all equations, the masses, the radii and the luminosities are in solar units.

3 High-mass X-ray Binaries

The orbital and stellar parameters of 13 High-mass X-ray binaries are given in Table 1 and Table 2 in Stoyanov & Zamanov (2009). We add 2 more objects - 4U 2206+54 and MWC 148. The orbital and stellar parameters are taken from Ribó et. al. (2006) and Casares et al. (2012) respectively.

Using Eq.2 and Eq.3 we estimate the circularization and synchronization timescales. The results are given in Table 1. The lifetime of a star on the main sequence can be estimated as $\tau_{MS} = 10^{10}(M_\odot/M)^{2.5}$ years (Hansen & Kawaler, 1994). Comparing these lifetimes with τ_{sync} from Table 1, we see that among the Be/X-ray binaries only for LSI+$61^0$303 is $\tau_{sync} \sim \tau_{MS}$. 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.

The lifetime of the giant is comparable or longer then τ_{circ} and τ_{sync} for the giant/supergiant systems with short orbital periods. The exceptions are V725 Tau and BP Cru, for which τ_{sync} and τ_{circ} are longer than the lifetime of the giant/supergiant stage.

On Fig.1 in Stoyanov & Zamanov (2009) is plotted P_{rot} versus P_{ps}. The giant/supergiant systems are located close to the line $P_{ps} = P_{rot}$, while those with mass donors from spectral class V are far away from the equilibrium.

In the Be/X-ray systems BQ Cam, V635 Cas, V725 Tau and 4U 2206+54, the tidal force spinning down the donor star. For the system LSI+$61^0$303, the rotation of the mass donor is close to pseudosynchronization. This is the only Be/X-ray binary in which τ_{sync} is comparable with the life-time of the binary. In the binaries X Per and MWC 148, the neutron star is far away from the Be star and the tidal force is weak.

Giant and supergiant systems are close to (pseudo)synchronization. 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 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+$65^0$010 and Vela X-1 are close to pseudosynchronization and the tidal force accelerates the rotation of the mass donors. 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 (Leahy & Kostka, 2008).

Table 1: Calculated time scales. Given here are the name of the object, synchronization time scale, circularization time scale, and the lifetime.

object	τ_{sync} [yr]	τ_{circ} [yr]	lifetime [yr]
Be/X-ray binaries			
LSI+61^{0}303*	2.8×10^7	2.4×10^8	5.6×10^7
X Per	6.2×10^{17}	1.8×10^{21}	1.1×10^7
BQ Cam	3.5×10^{11}	7.6×10^{13}	3.9×10^6
V635 Cas	1.4×10^{11}	9.5×10^{12}	7.3×10^6
4U 2206+54	4.9×10^9	3.7×10^{11}	7.3×10^7
MWC 148	1.2×10^{17}	5.1×10^{20}	9.8×10^7
Giant systems			
V725 Tau	2.8×10^{12}	8.0×10^{14}	4×10^5
LMC X-4	4.5×10^2	7.7×10^2	1×10^6
Cen X-3	2.3×10^3	4.2×10^3	5×10^5
Supergiant systems			
V830 Cen	7.5×10^3	1.4×10^4	1×10^6
LSI+65^{0}010	1.3×10^4	3.9×10^4	1×10^6
Vela X-1	1.0×10^4	2.8×10^4	3.9×10^5
SMC X-1	3.3×10^4	8.2×10^4	8.8×10^5
BP Cru	1.8×10^6	8.8×10^6	8×10^4
Cyg X-1	< 1	< 1	1×10^5

*assuming neutron star as a secondary component.

4 S-type Symbiotic Stars

43 symbiotic stars have been observed with FEROS spectrograph at the 2.2m ESO telescope of the La Silla Observatory (Zamanov et al. 2007). The data for the rotation of 55 field red giants are taken from the literature. M giants in S-type symbiotics rotate faster than the field M giants. Histograms of the available $v \sin i$ data for the red giants are plotted in Fig.2 in Zamanov & Stoyanov (2012). For the field M0III-M6III giants we calculate a mean $v \sin i$=5.0 km s^{-1}, median $v \sin i$=4.3 km s^{-1}, and standard deviation of the mean $\sigma = 4.0$ km s^{-1}. For the M0III-M6III giants in symbiotics, we get a mean $v \sin i$= 7.8 km s^{-1}, median $v \sin i$=8.0 km s^{-1}, and standard deviation of the mean σ =2.1 km s^{-1}.

There are 5 objects in our sample that deviate from the synchronization. These objects are RS Oph, MWC 560, CH Cyg, CD-43°14304 and Z And. In three of them collimated jets are detected: Z And (Skopal et al. 2009); CH Cyg (Crocker et al. 2002), MWC 560

(Tomov et al. 1990). Additionally to the jets, ejection of blobs are detected from RS Oph and CH Cyg (Iijima et al. 1994). This confirms the suggestions that in the jet-ejecting symbiotics the mass donors rotate faster than the orbital periods. Probably there is a link between the jets and the mass donor rotation.

On Fig.1 are plotted together the High-mass X-ray binaries and the S-type symbiotic stars. It shows that none of the objects in our sample is above the line of synchronization.
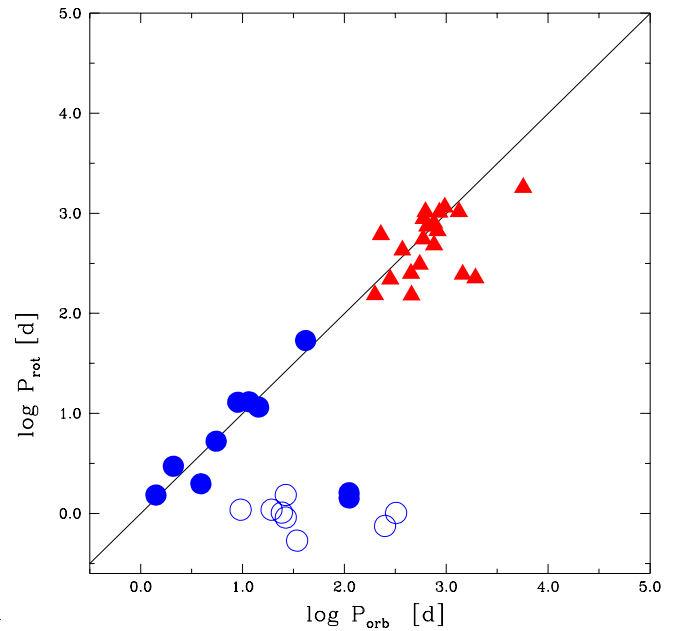

Figure 1: P$_{rot}$ versus P$_{orb}$ on a logarithmic scale. The blue circles indicates the High-mass X-ray Binaries - filled symbols for giant/supergiant systems and open symbols for Be/X-ray binaries. The red triangles indicates the S-type symbiotic stars.

5 Orbital Eccentricity of MWC 560

MWC 560 is a symbiotic star, which consists of a red giant and a white dwarf (Tomov et al. 1990). The most spectacular features of this object are the collimated ejections of matter with velocities of up to ~ 6000 km s^{-1} (Tomov et al. 1992) and the resemblance of its emission line spectrum to that of the low-redshift quasars (Zamanov & Marziani, 2002). The jet ejections are along the line of sight and the system is seen almost pole-on ($i < 16°$). This makes it difficult to obtain the orbital eccentricity of the system in a conventional way.

For the system we adopt $R_{\rm g} = 140 \pm 7\ R_\odot$, $L_{\rm g} \sim 2400\ L_\odot$, $M_{\rm g} = 1.7\ M_\odot$, $M_{\rm wd} = 0.65\ M_\odot$, $P_{\rm orb} = 1931 \pm 162$ day (Gromadzki et al. 2007), $R_{\rm env} = 0.9\ R_{\rm g}$

and $M_{\rm env} = 1.0 \ M_\odot$ (Herwig 2005). With the above values of the parameters assumed, we derive the semi-major axis of the orbit to be $a \approx 860 \ R_\odot$. Using these parameters, we calculate from Eq. 5 and Eq. 6 the synchronization and circularization time scales: $\tau_{\rm sync} = 2.6 \times 10^4$ yr and $\tau_{\rm circ} = 3.1 \times 10^6$ yr. The typical lifetime of a symbiotic star is $\tau_{\rm ss} \sim 10^5$ yr (Yungelson et al., 1995). From the rate of accretion on the white dwarf, $\dot{M}_{\rm acc} \approx 5 \times 10^{-7} \ M_\odot$ (Schmid et al. 2001), we can estimate, that it will take 10^6 yr to accrete $\sim 0.5 \ M_\odot$ from the envelope of the red giant companion. Because the giant also losses mass via stellar wind, we find that the lifetime of the symbiotic phase of MWC 560 should be $\tau_{\rm ss} \leq 10^6$ yr. For MWC 560 we have therefore the situation in which $\tau_{\rm ps} < \tau_{\rm syn} < \tau_{\rm ss} < \tau_{\rm circ}$. This means that the symbiotic phase is long enough that the tidal forces can (pseudo)synchronize the rotation of the red giant. On the other hand, the value of $\tau_{\rm circ}$ demonstrates that the symbiotic lifetime of MWC 560 is shorter than the circularization time, and therefore the orbit can be eccentric. This is in agreement with the observational evidences found by Fekel et al. (2007) that the symbiotic stars with $P_{\rm orb} > 800$ days tend to have eccentric orbits. The above implies that in MWC 560, the red giant is probably synchronized, but the orbit is not circularized. To determine the orbital eccentricity of MWC 560, we need to calculate $P_{\rm rot}$ for the mass donor. We analyzed 21 high resolution spectra of MWC 560 and obtained value for $v \ \sin i = 8.2 \pm 1.5$ km s^{-1}. Using $R_{\rm g} = 140 \pm 7 \ R_\odot$ and $i = 12^\circ - 16^\circ$, we calculate $P_{\rm rot} = 144 - 306$ days. This value is less than the orbital period. MWC 560 should be close to synchronization or pseudosynchronization, and $P_{\rm rot} = P_{\rm ps}$. Using Eq. 1 we can estimate the orbital eccentricity to be $e = 0.68 - 0.82$.

6 Conclusions

Using rotational velocity measurements and the theory of synchronization/pseudosynchronization we:

(1) find that the Be/X-ray binaries are far away from (pseudo)synchronization. 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 LSI+61⁰303. The objects containing mass donors of spectral class I and III typically have $P_{rot} \sim P_{ps}$ and are close to (pseudo)synchronization;

(2) demonstrate that the M giants in symbiotic stars rotate faster than the field giants. Most symbiotics with orbital period less than 1000 d are synchronized;

(3) show that the High-mass X-ray binaries and the S-type symbiotic stars are either on the line of synchronization or they are under the line. None of the objects in our sample is above the line of synchronization.

(4) calculate that the orbit of the symbiotic star MWC 560 should be highly eccentric, with $e \sim 0.7$.

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