Rotation of the red giants and white dwarfs in symbiotic binary stars

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Abstract. We discuss the rotation of the components in symbiotic binary stars. The new data confirm that (1) the M giants in symbiotics rotate faster than the field giants,(2) in the jet-ejecting symbiotics the mass donors have shorter periods of rotatins than the orbital periods. We also discuss the rotation of the white dwarfs in these binaries. Our expectations are that the low mass white dwarfs in short orbital period symbiotics have spin periods $P_{spin} \sim 30$ min, while massive white dwarfs and those in long orbital period systems $-P_{spin} \sim 10$ hr.
Key words: binaries: symbiotic – stars: late-type – X-rays: binaries – stars: individual: (RS Oph, CH Cyg, Z And, MWC 560)

1 Introduction

The Symbiotic stars (SSs) are thought to comprise a compact object (white dwarf or neutron star) accreting from a cool giant or Mira. Most symbiotics have orbital periods of a few years; some systems orbit over several decades. In these systems, the hot component accretes material lost by the red giant. This accreted material powers symbiotic activity, including outbursts, eruptions, dramatic episodic changes in the spectra, nonrelativistic jets and bipolar outflows (e.g. Kenyon 1986; Corradi, Mikołajewska &.Mahoney 2003). Binary systems consisting of a red giant and white dwarf are possible progenitors of type Ia supernovae. The small class of symbiotic recurrent novae containing red giants and white dwarfs of mass 1.3 $M_{\odot}$ are premier examples.

On the basis of their IR properties, SSs have been classified into stellar continuum (S) and dusty (D or D') types (Allen 1982). The D–type systems contain Mira variables as mass donors. The D'–type are characterized by an earlier spectral type (F-K) of the cool component and lower dust temperatures.

Here we summarize the explorations of the rotational periods of the cool components of symbiotic stars, and discuss the possible range of the spin periods of the white dwarfs in these binaries.

2 Observations

We have observed 43 objects from the Belczyński et al.(2000) SS catalogue with $0^h < RA < 24^h$, declination $< 2^0$, and catalogue magnitude brighter than $V < 12.5$.

The observations have been performed with FEROS at the 2.2m telescope of the La Silla Observatory (ESO programs 073.D-0724A and 074.D-0114). FEROS is a fibre-fed echelle spectrograph, providing a high resolution of $\lambda/\Delta\lambda$ =48000, a wide wavelength coverage from about 4000 Å to 8900 Å in one exposure and a high overall efficiency (Kaufer et al. 1999). The 39 orders of the echelle spectrum are registered with a 2k×4k EEV CCD All spectra are reduced using the dedicated FEROS data reduction software implemented in the ESO-MIDAS system. A few examples of our spectra are given in the Fig.1. All the spectra (including a few unpublished) are available on our server (http://195.96.237.247).

3 Fast rotation of the red giants in S-type symbiotics

To check the theoretical predictions that the red giant in symbiotic stars are fast rotators (Soker 2002; Ablimit & Lü 2012), we measured the projected rotational velocities ($v \sin i$) in a number of symbiotic stars and field giants. We also collected data from the literature for the rotation of the symbiotic stars.

For the D'-type (yellow) symbiotics, 5 out of the six southern D'-type SSs are the fastest or among the fastest rotators in their spectral classes. (Zamanov et al. 2006). The symbiotic K giants included in our survey rotate on average more than twice as fast as the field K giants (Zamanov et al. 2008).

M giants in S-type symbiotics are not so fast rotators but still rotate faster than the field giants. Histograms of the available $v \sin i$ data for red giants in the spectral range M0 - M6III are plotted in Fig.2. The data for the field giants in the interval M0III-M6III are collected from: 10 objects from Glebocki, Gnacinski & Stawikowski (2001), 4 from Hünsch et al.(2004) and 15 from Massarotti et al. (2008). Because we have found only 29 field M giants with measured $v \sin i$, we have searched in the archives for spectra of red giants. From the UVES Paranal Observatory Project (Bagnulo et al., 2003, ESO DDT Program ID 266.D-5655), we downloaded spectra of 17 M giants and from the ELODIE archive at Observatoire de Haute-Provence (Moultaka et al. 2004) we took spectra of 11 more objects. We applied the FWHM and CCF methods to measure the $v \sin i$ parameter in each case.

The $v \sin i$ data for symbiotic stars are from Schmutz et al. (1994), de Medeiros & Mayor (1999), Fekel, Hinkle & Joyce (2004), Zamanov et al. (2007). We add two more objects to them: CH Cyg [M6III, $v \sin i = 8 \pm 1$ km s^{-1} (Hinkle, Fekel & Joyce 2009)]; AE Ara [M5.5III (Mürset & Schmid 1999), $v \sin i = 8 \pm 1$ km s^{-1} (Fekel et al. 2010)].

The distributions of $v \sin i$ in the bin M0-M6III are plotted in Fig.2. For 55 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 33 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}.

The fastest rotator among M giants is the symbiotic star Hen 3-1674, which rotates almost at break-up velocity. This object in not plotted in the figure and not included in the calculation of the mean, because it is too far from the other values.

To confirm the visual impression (Fig. 2) that the symbiotic red giant rotates faster we apply mathematical/statistical approach. The Kolmogorov-Smirnov test gives a probability of only 2.8×10^{-7} (KS statistics =0.60) that both distributions arise from the same parent population. The comparison

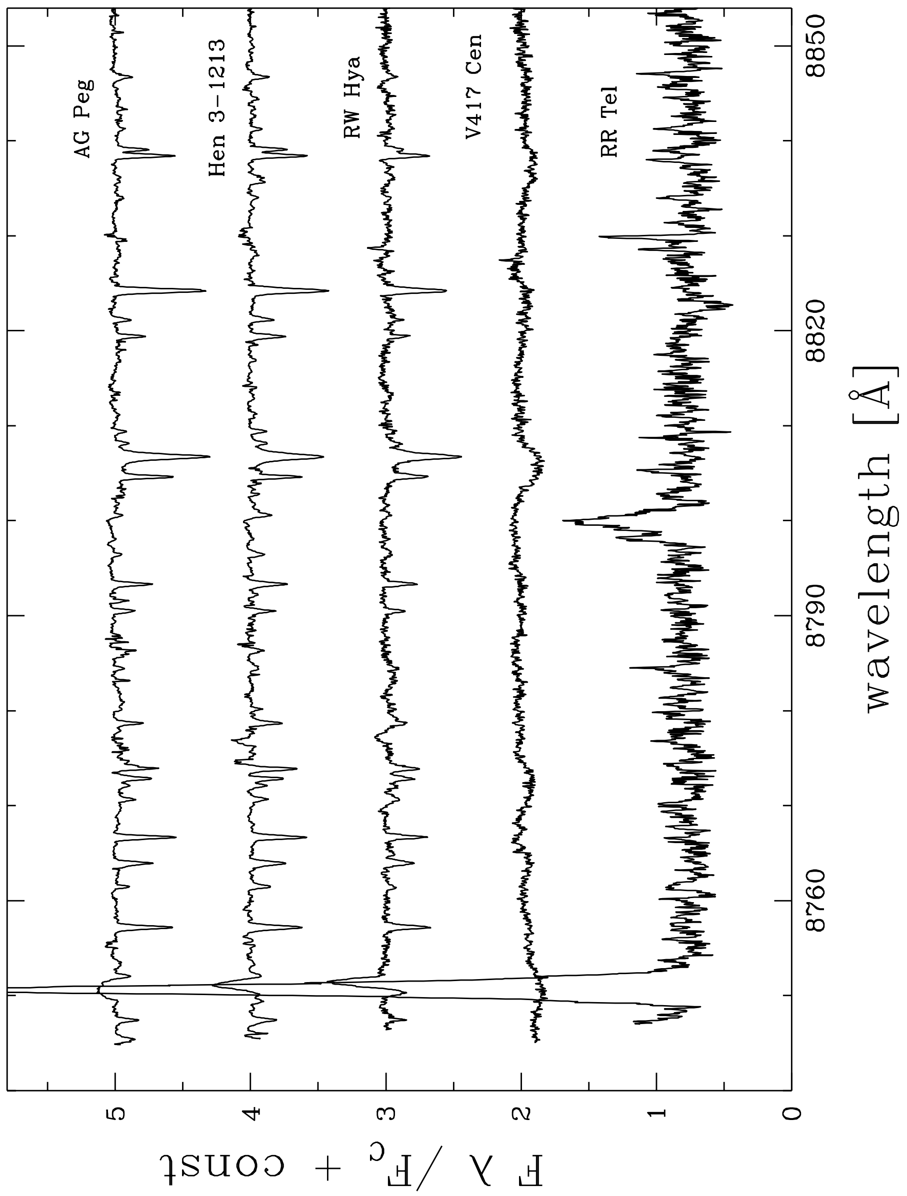

Fig. 1. A few examples of our spectra in the interval $\lambda\lambda 8740 - 8850$ Å. From up to down are plotted: RW Hya (S-type, M2III, $v \sin i$=7.1 ± 1.5 km s^{-1}), AG Peg (S-type, M4III, $v \sin i$=7.5 km s^{-1}), Hen 3-1213 (S-type, M2III, $v \sin i$=10.8±1.5 km s^{-1}), V417 Cen (D'-type, G9Ib-II, $v \sin i$=75 ±8 km s^{-1}), RR Tel (D-type, symbiotic nova, symbiotic Mira).

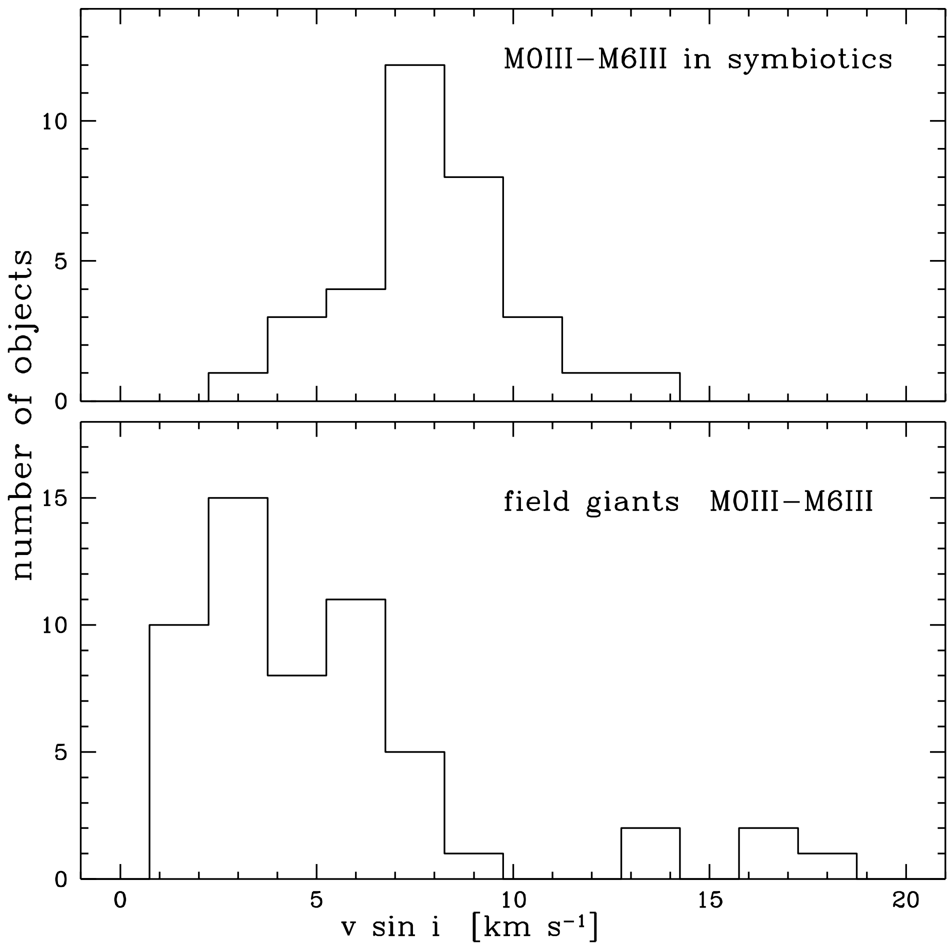

Fig. 2. The distribution of the projected rotational velocity ($v\ \sin i$) for M0-M6 giants in symbiotic binaries (upper panel) compared to the distribution for the field M giants (bottom panel)

of the medians (Mann-Whitney U-test) for the symbiotic and single giants gives a probability of the median $v\ \sin i$ of the symbiotic giants being higher than that of the field giants > 0.99999 (U statistics = 1494.5). Both tests give that the difference between the two samples is highly significant ($p << 0.001$), making statistically sure that the red giants in S-type symbiotics rotate faster than the field M giants. As a result of the rapid rotation SSs should have larger mass loss rates than normal red giants.

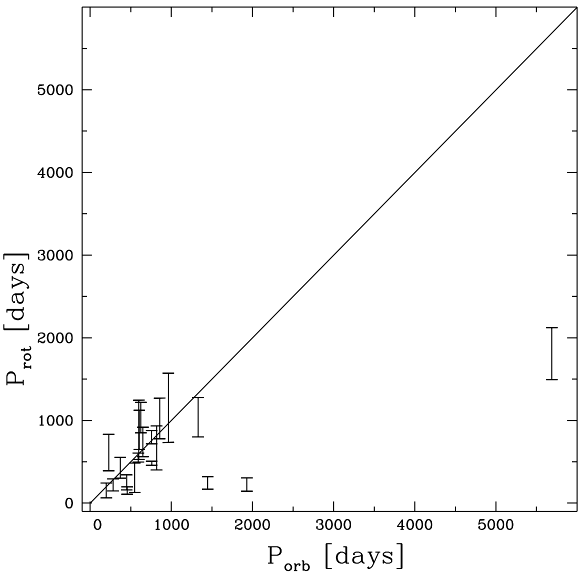

Fig. 3. The rotational period of the red giant (P_{rot}) versus the orbital period (P_{orb}) of the 21 objects in our sample. The solid line corresponds to $P_{rot} = P_{orb}$. Most objects are close to this line, which indicates that they are synchronized.

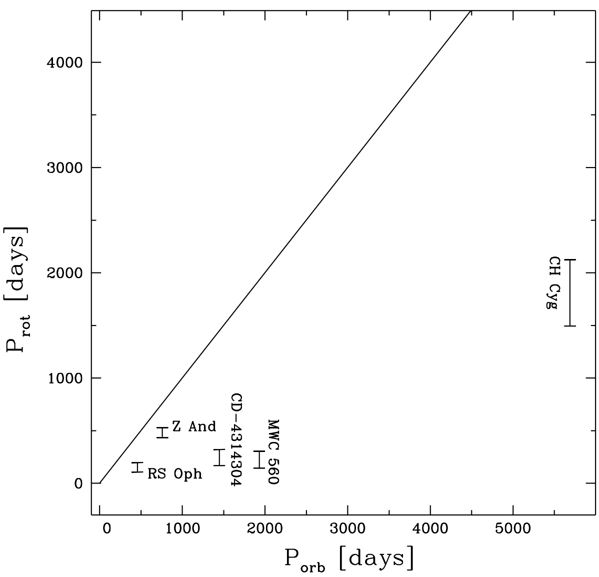

Fig. 4. The rotational period of the red giant (P_{rot}) versus the orbital period (P_{orb}) for objects deviating from the synchronization rule.

Table 1. Rotational periods of the red giants in S-type symbiotic stars with known orbital periods. In the table name of the object, orbital period, P_{orb}, the rotational period of the red giant, P_{rot}, are given.

object	P_{orb} [d]	P_{rot} [d] min - max	Ref.
BF Cyg	757.3	798±40	1
CH Cyg	5689.2	1810±180	2
Z And	759.0	482±20	3
YY Her	593.2	551±30	4
AR Pav	604.5	887±200	5
V343 Ser	450.2	250±90	5
BD-21^{0}3873	281.6	220±70	5
RS Oph	455.5	152±40	5
RW Hya	370.4	427±120	5
FG Ser	650	741±170	5
CD-43 14304	1448	246±70	5
SY Mus	624.5	1035±180	5
AG Dra	548.5	308±170	5
TX CVn	199	153±80	5
AG Peg	818.2	667±200	5
V1329 Cyg	963.1	1153±400	5
T CrB	227.57	612±220	5
BX Mon	1330	1039±200	5
V443 Her	599.4	887±300	5
CI Cyg	855.6	1025±200	5
MWC 560	1931.0	225±80	6

References: 1 - Leibowitz & Formiggini (2006), 2 - Hinkle et al. (2009), 3 - Leibowitz & Formiggini (2008), 4 - Formiggini & Leibowitz (2006), 5 - Zamanov et al. (2007), 6 - Zamanov et al. (2010).

Table 2. The spin period of the compact objects in symbiotic stars.

object	components	P_{spin}	P_{orb} [d]	Ref.
ZAnd	M2 III+WD	1682.6±0.6 s	758.8	1,10
BFCyg	M5 III+WD	1.806±0.114 hr	757.2	2,9
V2116 Oph (GX 1+4)	M5 III + NS	110-160 s	1161	11,3
3A1954+319 (4U 1954+31)	M4.5 III + NS	5.3 hr		4
4U1700+24 (V934 Her)	M2 III + NS	900 s	404	5,6
IRXSJ180431.1-273932	K-M III + NS	494 s		7
IGR J16393-4643	K-M III + NS	912 s	50.2?	8,15
Sct X-1 (AX J1835.4-0737)	K-M I-III + NS	110-112 s		12
IGR J16358-4726	K-M III + NS	5850 s		13,8
2XMM J174016.0-290337	K1 III + NS	626 s		14

References: 1 - Sokoloski & Bildsten (1999), 2 - Formiggini & Leibowitz (2009), 3 - Hinkle et al. (2006), 4 - Marcu et al.(2011) 5 - Morgan & Garcia (2001), 6 - Masetti et al. (2006), 7 - Nucita, Carpano & Guainazzi (2007). 8 - Nespoli, Fabregat & Mennickent (2010), 9 - Fekel et al. (2001), 10 - Fekel et al.(2000), 11 - González-Galán et al.(2012), 12 - Kaplan et al. (2007), 13 - Patel et al. (2004), 14 - Farrell et al. (2010), 15 - Bodaghee et al.(2006).

4 Synchronization

Till now, both orbital period and rotational period of the red giant are known for 21 SSs. The available data are collected in Table 1. Fig. 3 shows the rotational period versus the orbital period of the 21 objects in our sample, with a straight line indicating the co-rotation (i.e. P_{rot}=P_{orb}). Most objects are close to this line, which suggests that they are synchronized.

The Spearman rank correlation coefficient between the two periods is 0.51 when all 21 objects were included, and about 0.84 for 16 objects (when we remove the deviating objects, see below). This result implies a significant correlation between the variables, since the p-values are less than 0.02 and 0.0001 respectively. The similar Kendall-tau test gives similar results, with p-values less than 0.02 and 0.001 for 21 and 16 objects respectively.

Our result show that there are no sources, which are above the line of synchronization. However we do detect sources in which $P_{rot} < P_{orb}$. There are 5 objects in our sample that deviate from the synchronization. The 4 objects that are outside of the 3-σ level are RS Oph, MWC 560, CH Cyg and CD-43°14304. Z And is (almost) at 3-σ level. In three of them collimated outflows (jets) are detected: Z And (Skopal et al. 2009 ; Burmeister & Leedjärv 2007); CH Cyg (precessing jets, 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; Zajczyk et al. 2008).

This confirms our early suggestions that in the jet-ejecting symbiotics the mass donors rotate faster than the orbital periods. It points to an unexpected result that there is a link between the jets and the mass donor rotation. This is probably somehow connected to the angular momentum accretion rate.

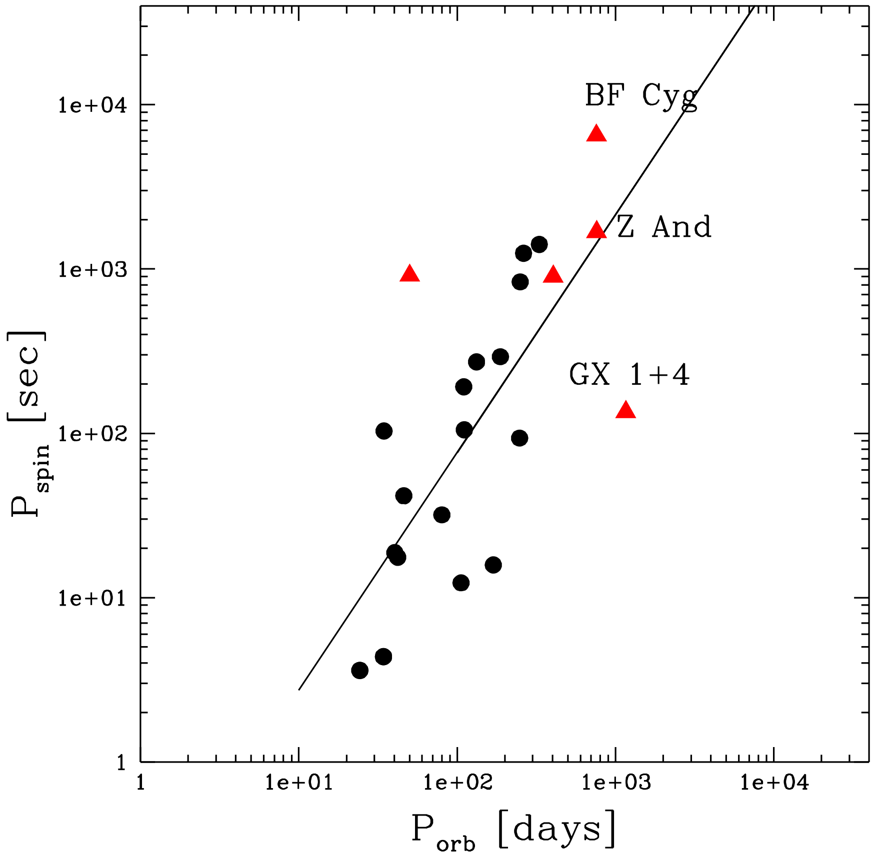

Fig. 5. The Corbet diagram (P_{spin} versus P_{orb}). The (black) circles represent the Galactic Be X-ray binaries, the (red) triangles - the symbiotic stars.

5 Rotation of the white dwarfs in symbiotic stars

While we already know a lot about the rotation of the mass donating cool components in symbiotic stars, the rotation of the white dwarfs remains unexplored yet. Till now, there are only two white dwarfs in symbiotic stars with measured spin periods: Z And and BF Cyg. Here we attempt to predict to what spin periods of the white dwarfs in symbiotic stars could be.

In Table 2 the data for the symbiotic stars for which the spin period of the compact object is known are collected In Fig. 5 we plot P_{spin} versus P_{orb}. This is so named Corbet diagram (Corbet 1986). The (black) circles represent the Galactic Be/X-ray binaries from the compilation of Reig (2011). The (red) triangles are the symbiotic stars.

5.1 Disk accretion

Livio & Pringle (1998) have examined the question of why the white dwarfs in dwarf nova systems are found to be rotating much more slowly than expected. They have proposed a model in which the accreted angular momentum is removed during nova outbursts.

Let us suppose that the WDs in symbiotic systems accrete matter from an accretion disk. The specific angular momentum of the accreted matter is $j = (GM_{WD}R_{WD})^{1/2}$, where M_{WD} and R_{WD} are the mass and radius of the WD. If we start with a non-rotating WD of initial mass M_0, which accretes until its mass achieves M_1 ($M_1 = M_0 + \Delta M$) and its angular velocity achieves Ω, then (e.g., Papaloizou & Pringle 1978):

$$\Omega = \Omega_K \, \frac{3}{4r_g^2} \, \left(1 - \left(\frac{M_0}{M_1}\right)^{4/3}\right), \tag{1}$$

where r_g is the gyration radius of the WD, Ω_K is the critical Keplerian angular velocity of a WD:

$$\Omega_K = \left(\frac{GM_{WD}}{R_{WD}^3}\right)^{1/2}. \tag{2}$$

Using this and assuming that the nova explosion removes the accreted angular momentum, we make a rough estimate of the expected rotation of the WD in symbiotic stars. For the onset of TNR the pressure on the base of the accreted envelope must achieve a value of $\approx 2\times10^{19}$ dyne cm^{-2} (Fujimoto 1982). Using the Suh & Mathews (2000) relation between mass and radius for a ^{12}C white dwarf, we calculate the necessary mass of the envelope for ignition of TNR, ΔM_{TNR}, listed in column 3 of Table 3. After it using Eq.1, we calculate the expected spin period of the white dwarfs in symbiotic stars. The expected P_{spin} are listed in column 4 of Table 3.

In the frame of disk accretion, we expect the massive white dwarfs to have longer spin periods. The massive white dwarfs in the recurrent novae RS Oph and T CrB probably have spin periods $\sim$ 1 day. In MWC 560 $M_{WD} \approx 0.92 \pm 0.07$ (Zamanov, Gomboc, Latev 2011) and we expect P_{spin} $\sim$50 min.

In BF Cyg M_{WD} = 0.51 $M_\odot$ (Mikołajewska 2003) and the observed P_{spin}=108 min is considerably longer than our expectations. However, in Z And the white dwarf has $M_{WD} = 0.65 \pm 0.28$ $M_\odot$ (Schmid & Schild 1997) and P_{spin}=28 min, which is in agreement with our expectations in Table 3.

5.2 Quasi-spherical accretion

Symbiotic X-ray Binaries (SyXBs) are new sub-class of persistent Low-mass X-ray Binaries (LMXBs) in which a neutron star is orbiting in the inhomogeneous medium around an M-type giant star (Masetti et al., 2006). For the symbiotic X-ray binary star GX 1+4, Gonzàlez-Galàn et al. (2012) provide a model of quasi-spherical accretion onto the neutron star from the stellar wind of the red giant. According to the model, in wind-fed pulsars with long orbital

Table 3. The expected spin period of the WDs in symbiotic stars. In the Table WD mass, WD radius, necessary mass of the envelope for ignition of TNR, ΔM_{TNR}, and the expected spin period of the WD are given.

M_{WD} [$M_\odot$]	R_{WD} [km]	ΔM_{TNR} [$M_\odot$]	P_{spin} expected [disc accretion]	P_{spin} expected [quasi-spherical]
0.40	10400	2.80×10^{-3}	3 - 6 min	0.3 - 15 hr
0.50	9200	1.36×10^{-3}	5 - 11 min	...
0.60	8350	7.64×10^{-4}	9 - 18 min	...
0.70	7650	4.62×10^{-4}	14 - 28 min	...
0.80	6800	2.55×10^{-4}	23 - 46 min	...
0.90	6120	1.47×10^{-4}	36 - 72 min	0.3 - 15 hr
1.00	5360	7.77×10^{-4}	58 - 116 min	...
1.10	4660	4.05×10^{-4}	95 - 190 min	...
1.20	3830	1.68×10^{-4}	3 - 6 hr	...
1.30	2780	4.35×10^{-4}	7 - 14 hr	...
1.35	2090	1.33×10^{-4}	16 - 32 hr	0.3 - 15 hr

periods, accretion onto the neutron star can proceed quasi-spherically and an accretion disk around the neutron star magnetosphere cannot be formed at all.

The accretion disk formation depends on whether the specific angular momentum of matter j_m near the magnetospheric radius R_m is larger or smaller than of the Keplerian value j_K (R_m) $= \sqrt{GMR_m}$. Assuming the specific angular momentum conservation, j_m can be related to that of gravitationally captured stellar wind matter in the zone of bow shock at the Bondi radius R_G = 2GM/($V_W^2 + V_{orb}^2$). The specific angular momentum of matter j_m give us a clue to estimate the expected P_{spin} of the white dwarf in case of quasi-spherical accretion.

The specific angular momentum j_a of the captured stellar wind matter is

$$j_a = k_w \Omega_{orb} R_G^2 = k_w \frac{2\pi}{P_{orb}} R_G^2, \tag{3}$$

where R_G is the radius of the gravitational capture (the Bondi radius), $\Omega_{orb} = 2\pi/P_{orb}$ is the orbital frequency. k_w is a numerical coefficient. Illarionov & Sunyaev (1975) supposed $k_w \sim 0.25$. The numerical experiments demonstrate that it could be variable and lower (Sawada et al. 1989; Foglizzo, Galletti & Ruffert 2005; Dönmez, Zanotti & Rezzolla 2011). The equilibrium spin period of the accreting objects is:

$$P_{spin} = \frac{2\pi R_{stop}}{V_\phi} \tag{4}$$

where V_ϕ is the transverse velocity of the accreting matter at distance R_{stop} from the accreting object, defined by

$$V_\phi R_{st} = j_a. \tag{5}$$

The equilibrium spin period is

$$P_{spin} = \frac{R_{stop}^2}{k_w R_G^2}\ P_{orb}. \tag{6}$$

This equation explains the observed strong dependence of P_{spin} from P_{orb} in wind fed binaries (Fig.5).

The scatter in Fig. 5 is (probably) due to R_{st}, k_w and R_G, which differ from object to object depending on the velocity, density, temperature of the wind, accreting object velocity, its magnetic field, etc. We expect that R_G and k_w also depend on P_{orb}. However the general trend is a linear dependence of P_{spin} from P_{orb} in agreement with Eq.6.

We should note that: (1) in the case of magnetized object (neutron star or magnetic white dwarf) $R_{stop} = R_A$, where R_A is the Alfvén radius (radius of the magnetosphere); (2) in the case of non magnetic white dwarf $R_{st} \approx 3R_{WD}$, i.e. approximately the size of the boundary layer around the white dwarf.

Our expectations are that the P_{spin} of the white dwarfs in symbiotic stars follow roughly the relation:

$$\log P_{spin} = -1.011 + 1.447\ \log P_{orb}. \tag{7}$$

This is the best linear fit to all data points in (Fig. 5). This fit is used to calculate the likely P_{spin} for the case of quasi-spherical accretion as listed in Table 3. The shorter P_{spin} refers to short orbital period (≈300 d) while the longer – to $P_{orb} \approx 5000$ d.

Conclusions

The main results reported here are:

1. We confirm that the M giants in SSs rotate faster than the field giants.
2. Most symbiotics with orbital period less than 1000 d are synchronized.
3. We obtain a strange result: in the jet-ejecting symbiotics the mass donors have periods of rotation shorter than the orbital periods.
4. We give clues to what the spin periods of the white dwarf in symbiotic stars could be. In our predictions, it is expected that the low mass white dwarfs in short orbital period symbiotics should have $P_{spin} \sim 30$ min, while massive white dwarfs and those in long orbital period systems $P_{spin} \sim 10$ hr.

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