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Orbital eccentricity of the symbiotic star MWC 560*

R.K. Zamanov[1,**], **A. Gomboc**[2], **K.A. Stoyanov**[1], and **I.K. Stateva**[1]

[1] Institute of Astronomy, Bulgarian Academy of Sciences, 72 Tsarigradsko Shousse Blvd., 1784 Sofia, Bulgaria
[2] Faculty of Mathematics and Physics, University of Ljubljana, Jadranska 19, 1000 Ljubljana, Slovenia

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We present projected rotational velocity measurements of the red giant in the symbiotic star MWC 560, using the high-resolution spectroscopic observations with the FEROS spectrograph. We find that the projected rotational velocity of the red giant is $v \sin i = 8.2 \pm 1.5$ km s^{-1}, and estimate its rotational period to be $P_{\rm rot}$ = 144–306 days. Using the theoretical predictions of tidal interaction and pseudosynchronization, we estimate the orbital eccentricity $e = 0.68 - 0.82$. We briefly discuss the connection of our results with the photometric variability of the object.

1 Introduction

MWC 560 (V694 Mon) was discovered as an object with bright hydrogen lines (Merrill & Burwell 1943). It is a symbiotic binary system, which consists of a red giant and a white dwarf (Tomov et al. 1990; Michalitsianos et al. 1993). The orbital period is supposed to be $P_{\rm orb} \approx 5.3$ yr (Doroshenko, Goranskij & Efimov 1993). The most spectacular features of this object are the collimated ejections of matter with velocities of up to $\sim$6000 km s^{-1} (Tomov et al. 1992; Stute & Sahai 2009) and the resemblance of its emission line spectrum to that of 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 parameters using the radial velocity variations, and impossible to observe effects such as eclipse or illumination.

To improve our understanding of this object, we aim here to: (1) measure the projected rotational velocity of the red giant ($v \sin i$) from high resolution spectra, and (2) use our measured $v \sin i$ to find the eccentricity e of the orbit, on the basis of the theory for pseudosynchronization in binary stars.

2 Spectral data and $v \sin i$ measurement

2.1 Observations

We analyzed 21 high resolution spectra of MWC 560, obtained with the FEROS spectrograph. FEROS is a fiber fed echelle spectrograph, providing high resolution of $\lambda/\Delta\lambda = 48\,000$ and an wide wavelength coverage from about 4000 Å to 8900 Å in one exposure (Kaufer et al. 1999). 16 of the analyzed spectra are from our observations of the MWC 560 with the 2.2-m telescope at ESO, La Silla (ESO program 074.D-0114). The remaining spectra (5), are downloaded from FEROS Spectroscopic Database at the LSW Heidelberg[1] and were obtained when FEROS was mounted on the 1.52-m telescope at La Silla. A log of observations is given in Table 1. Details of the data processing are given in Zamanov et al. (2007). In Fig. 1 we show the average spectrum derived from the 16 spectra obtained by 2.2-m telescope.

Symbiotic stars have composite spectra with three main sources of radiation – red giant, hot component and nebula. Modeling of a few objects is given in Skopal (2005). Figure 1 also shows a synthetic spectrum of a M5III star with following parameters: $T_{\rm eff} = 3424$ K, $\log g = 0.5$, $\xi = 3$ km s^{-1}, $v \sin i$ = 8.2 km s^{-1}, and with a 64% contribution of the giant at $\lambda = 8800$ Å (see Sect. 2.2.).

2.2 $v \sin i$ measurement

We measure $v \sin i$ by comparing the FWHM of spectral lines of observed and synthetic spectra. The procedure is similar to that described in Fekel (1997).

We synthesized spectra by using the code SYNSPEC (Hubeny, Lanz & Jeffery 1994) in the spectral region λ = 8750–8850 Å. Atmospheric parameters $T_{\rm eff} = 3424$ K, $\log g = 0.5$ (typical for a M5III star, see van Belle et al. 1999), the instrumental profile for our FEROS spectra, and solar abundances were the input parameters for the code. LTE model atmospheres were extracted from Kurucz's grid (1993). The VALD atomic line database (Kupka et al. 1999) was used to create a line list for spectrum synthesis.

We adopt a microturbulent velocity $\xi = 3$ km s^{-1}. This value is the same as accepted by Fekel, Hinkle & Joyce

* based on observations obtained in ESO program 074.D-0114
** Corresponding author: rkz@astro.bas.bg

[1] www.lsw.uni-heidelberg.de/projects/instrumentation/Feros/ferosDB/

Table 1 Spectral observations of MWC 560. The columns in the table represent: Column 1 the modified Julian Date (MJD) of the start of the exposure, Col. 2 the exposure time, and Col. 3 the measured projected rotational velocity ($v \sin i$) of the mass donor.

MJD	Exp. Time [s]	$v \sin i$ [$\mathrm{km\,s^{-1}}$]
2.2-m telescope		
53314.279	300	8.5
53314.283	300	8.6
53314.287	300	7.9
53314.291	300	7.8
53314.295	300	8.0
53314.299	300	8.2
53314.303	300	8.2
53314.308	300	8.5
53314.312	300	8.8
53314.316	300	7.8
53314.320	300	8.3
53314.324	300	7.7
53314.328	300	8.6
53314.332	300	7.9
53314.336	300	8.1
53314.340	300	8.5
1.52-m telescope		
51133.223	1200	7.8
51131.248	2400	8.9
51135.283	1200	7.8
51136.259	900	7.9
51141.315	1200	8.2

(2004) and it is close to the values for other symbiotics. Schmidt et al. (2006) calculated $\xi = 2.2\ \mathrm{km\,s^{-1}}$ for CH Cyg. Wallerstein et al. (2008) used $\xi = 2.2\ \mathrm{km\,s^{-1}}$ for T CrB. The relation between ξ and $\log g$ (Gratton, Carretta & Castelli 1996) gives $\xi \approx 2.1\ \mathrm{km\,s^{-1}}$ for our case.

A grid of synthetic spectra for projected rotational velocities from 0 $\mathrm{km\,s^{-1}}$ to 20 $\mathrm{km\,s^{-1}}$ was calculated, and $v \sin i$ was determined by measuring the full width at half maximum (FWHM) of twelve observed spectral lines. These were compared to the spectral line half-widths from the synthetic spectra. We thereby derive a mean $v \sin i = 8.2\ \mathrm{km\,s^{-1}}$, and a standard deviation of the mean, $\sigma = 0.4\ \mathrm{km\,s^{-1}}$, using all 21 spectra. We note that if we adopt a microturbulent velocity $\xi = 2\ \mathrm{km\,s^{-1}}$ we would have measured $v \sin i = 9.4\ \mathrm{km\,s^{-1}}$. For the error of our measurements we adopt a conservative value $\pm 1.5\ \mathrm{km\,s^{-1}}$, which also includes the uncertainty of $\xi = 3 \pm 0.5\ \mathrm{km\,s^{-1}}$ and the error of our method. We therefore estimate our final measurement to be $v \sin i = 8.2 \pm 1.5\ \mathrm{km\,s^{-1}}$.

3 Tidal interaction in MWC 560

3.1 Parameters of MWC 560

Meier et al. (1996) classified the cool component of MWC 560 as M5III–M6III giant. Mürset & Schmid (1999) give M5.5III–M6III as its stellar type. According to van Belle et al. (1999), a typical M5III giant has the following parameters: $R_\mathrm{g} = 139.6 \pm 5.6\ \mathrm{R_\odot}$, $T_\mathrm{eff} = 3424$ K, $L_\mathrm{g} \sim 2410\ \mathrm{L_\odot}$, and a typical M6III giant: $R_\mathrm{g} = 147.9 \pm 7.7\ \mathrm{R_\odot}$, $T_\mathrm{eff} = 3375$ K, $L_\mathrm{g} \sim 2560\ \mathrm{L_\odot}$. We adopt for the M giant in MWC 560 $R_\mathrm{g} = 140 \pm 7\ \mathrm{R_\odot}$ and $L_\mathrm{g} \sim 2400\ \mathrm{L_\odot}$.

For the masses of the red giant and white dwarf we will assume $M_\mathrm{g} = 1.7\ \mathrm{M_\odot}$ and $M_\mathrm{wd} = 0.65\ \mathrm{M_\odot}$, respectively. These values are the average masses of the components of the symbiotic stars (Mikołajewska 2003). Concerning the orbital period, we use $P_\mathrm{orb} = 1931 \pm 162$ d (Gromadzki et al. 2007). With the above values of the parameters assumed, we derive the semimajor axis of the orbit to be $a \approx 860\ \mathrm{R_\odot}$.

The jet (orbit) inclination angle to the line of sight is $i < 16^\circ$, and the white dwarf accretes at a rate $\dot{M}_\mathrm{acc} \approx 5 \times 10^{-7}\ \mathrm{M_\odot}$ (Schmid et al. 2001).

3.2 Synchronization and circularization time scales

The physics of tidal synchronization for stars with convective envelopes has been analyzed several times. There are some differences in the analysis of different authors, leading to varying synchronization timescales. We use the estimate from Zahn (1977, 1989). The synchronization timescale in terms of the period is

$$\tau_\mathrm{syn} \approx 800 \left(\frac{M_\mathrm{g} R_\mathrm{g}}{L_\mathrm{g}} \right)^{1/3} \frac{M_\mathrm{g}^2 (\frac{M_\mathrm{g}}{M_\mathrm{wd}} + 1)^2}{R_\mathrm{g}^6} P_\mathrm{orb}^4 \quad [\mathrm{yr}], \quad (1)$$

where M_g and M_wd are the masses of the giant and white dwarf respectively in solar units, and R_g, L_g are the radius and luminosity of the giant, also in solar units. The orbital period P_orb is measured in days.

Following Hurley, Tout & Pols (2002), the circularization time scale is

$$\frac{1}{\tau_\mathrm{circ}} = \frac{21}{2} \left(\frac{k}{T} \right) q_2 (1 + q_2) \left(\frac{R_\mathrm{g}}{a} \right)^8, \quad (2)$$

where q_2 is the mass ratio $q_2 = M_\mathrm{wd}/M_\mathrm{g}$, In Eq. (2), (k/T) is derived from Rasio et al. (1996):

$$\left(\frac{k}{T} \right) = \frac{2}{21} \frac{f_\mathrm{conv}}{\tau_\mathrm{conv}} \frac{M_\mathrm{env}}{M_\mathrm{g}} \quad [\mathrm{yr}^{-1}], \quad (3)$$

where R_env is the depth of the convective envelope, M_env is the envelope's mass, and

$$\tau_\mathrm{conv} = 0.4311 \left(\frac{M_\mathrm{env} R_\mathrm{env} (R_\mathrm{g} - \frac{1}{2} R_\mathrm{env})}{3 L_\mathrm{g}} \right)^{\frac{1}{3}} \quad [\mathrm{yr}] \quad (4)$$

is the eddy turnover time scale (the time scale on which the largest convective cells turnover). The numerical factor f_conv is

$$f_\mathrm{conv} = \min \left[1, \left(\frac{P_\mathrm{tid}}{2\tau_\mathrm{conv}} \right)^2 \right], \quad (5)$$

where P_tid is the tidal pumping time scale given by

$$\frac{1}{P_\mathrm{tid}} = \left| \frac{1}{P_\mathrm{orb}} - \frac{1}{P_\mathrm{rot}} \right|. \quad (6)$$

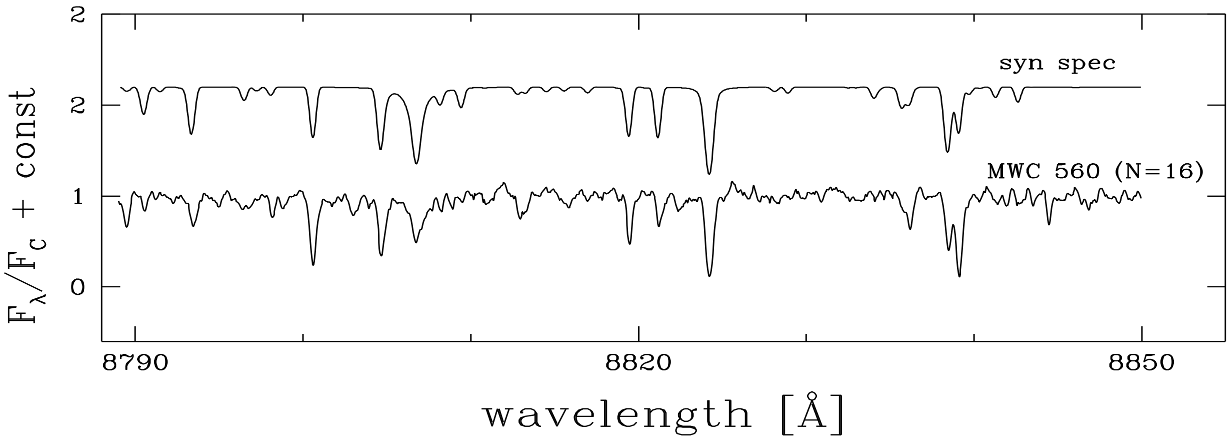

Fig. 1 The average spectrum of MWC 560 in the range $\lambda = 8790$–8850 Å, obtained from 16 exposures with the FEROS spectrograph at the 2.2-m telescope at La Silla, and a synthetic spectrum using $T_{\rm eff} = 3424$ K, $\log g = 0.5$, $\xi = 3$ km s^{-1}, $v \sin i = 8.2$ km s^{-1}, and a 64% contribution from the giant.

For MWC 560 we assume for the red giant to have $R_{\rm env} = 0.9\ R_{\rm g}$ and $M_{\rm env} = 1.0\ {\rm M}_\odot$ (Herwig 2005). Using these parameters, we calculate $P_{\rm tid} = 248$ d, $f_{\rm conv} = 1$, $\tau_{\rm conv} = 0.476$ yr, and $(k/T) = 0.12$ yr^{-1}. Then from Eqs. (1) and (2) follow that the synchronization and circularization time scales are $\tau_{\rm sync} = 2.6 \times 10^4$ yr and $\tau_{\rm circ} = 3.1 \times 10^6$ yr, respectively.

Following Hut (1981), we estimate the pseudosynchronization timescale $\tau_{\rm ps}$ as

$$\tau_{\rm ps} = \frac{7}{3(\alpha - 3)} \tau_{\rm circ}, \qquad (7)$$

where α is a dimensionless quantity, representing the ratio of the orbital and rotational angular momentum,

$$\alpha = \frac{q_2}{1 + q_2} \frac{1}{r_{\rm g}^2} \left(\frac{a}{R_{\rm g}} \right)^2, \qquad (8)$$

where $r_{\rm g}$ is the gyration radius of the giant. For a red giant we adopt $r_{\rm g} \approx 0.3$ (Claret 2004, 2007). We calculate $\alpha = 800$ and $\tau_{\rm ps} = 9.1 \times 10^3$ yr.

3.3 Lifetime of the symbiotic phase

The typical lifetime of a symbiotic star is $\tau_{\rm ss} \sim 10^5$ yr (Yungelson et al. 1995; Lü, Yungelson & Han 2006). In the case of MWC 560, we can estimate from the rate of accretion on the white dwarf, $\dot{M}_{\rm acc} \approx 5 \times 10^{-7}\ {\rm M}_\odot$ (Schmid et al. 2001), that it will take 10^6 yr to accrete $\sim 0.5\ {\rm M}_\odot$ 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 $\tau_{\rm ss} \lesssim 10^6$ 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 synchronize (pseudosynchronize) 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.

Schmutz et al. (1994) estimated that the timescale for circularization in SY Mus is ~ 10 times longer then the synchronization time. For MWC 560, we find even higher ratio: $\tau_{\rm circ}/\tau_{\rm syn} \approx 45$.

The above implies that in MWC 560, the red giant is probably more or less synchronized, but the orbit is not circularized.

3.4 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, $P_{\rm rot} = P_{\rm orb}$. However, 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 – the effect called pseudosynchronous rotation (Hall 1986). The corresponding equilibrium (i.e. pseudosynchronization) is reached at a value of $P_{\rm rot}$ which is *less* than $P_{\rm orb}$, the amount less being a function of the orbital eccentricity e. Hut (1981) showed that the period of pseudosynchronization, $P_{\rm ps}$, is

$$P_{\rm ps} = \frac{(1 + 3e^2 + \frac{3}{8}e^4)(1 - e^2)^{\frac{3}{2}}}{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6} P_{\rm orb}\,. \qquad (9)$$

When the eccentricity tends to zero, $P_{\rm ps}$ tends to $P_{\rm orb}$.

3.5 Orbital eccentricity of MWC 560

In order to determine the orbital eccentricity of MWC 560, we first need to calculate $P_{\rm rot}$ for the mass donor. We use

$$P_{\rm rot} = \frac{2\pi R_{\rm g} \sin i}{v \sin i}\,. \qquad (10)$$

The underlying assumption is that the rotational axis of the mass donor is perpendicular to the orbital plane.

Using the value for $v \sin i = 8.2 \pm 1.5$ km s^{-1} (Sect. 2), $R_{\rm g} = 140 \pm 7\ {\rm R}_\odot$, and $i = 12°$–$16°$ (Schmid et al. 2001), we calculate $P_{\rm rot} = 144$–306 d. This value is considerably less than the orbital period, $P_{\rm orb} = 1931 \pm 162$ d. Following the results in Sect. 3.2, MWC 560 should be close to synchronization or pseudosynchronization, and $P_{\rm rot} = P_{\rm ps}$. Finally, using Eq. (9) we can therefore estimate the orbital eccentricity to be $e = 0.68$–0.82.

4 Discussion

In most of the symbiotics the activity of the hot components is irregular/aperiodic. However, in MWC 560 it has a periodic character. An analysis of the historical light curve (Luthardt 1991) and B-band photometry, as well as the periodogram analysis of V-band and near-IR observations reveal that this periodicity has remained in-phase for over a century (Doroshenko et al. 1993; Gromadzki et al. 2007). The most natural explanation for this phenomenon is orbital modulation: around periastron, the mass accretion rate increases, which causes an increase of the accretion luminosity and the brightness of the accretion disk, which produces the observed modulation of the light curves (see also Doroshenko et al. 1993; Gromadzki et al. 2007).

With the parameters assumed above, we can calculate the distance between the components at the periastron: $r_{\rm p} = a(1-e) = 180$–230 $\rm R_\odot$. It follows that the red giant fills the Roche lobe for about 5–25 % of the orbital period. This is in agreement with the suppositions of Gromadzki et al. (2007), that the orbital eccentricity and corresponding Roche lobe overflow at the periastron is the reason for the observed photometric variability.

It has been noted that the rotational period of the mass donor is considerably shorter than the orbital period (Zamanov et al. 2008) in a few jet-ejecting symbiotics. Our findings here pose the question whether their orbits are also eccentric.

Conclusions

In this note, we presented new measurements of the projected rotational velocity of the red giant in the symbiotic star MWC 560. We find that $v \sin i = 8.2 \pm 1.5$ km s^{-1}. On the basis of the theory of tidal interaction in binaries, we calculate that the orbit should be highly eccentric, with $e \gtrsim 0.7$. Our findings support the model that the observed photometric variability of MWC 560 is connected with high orbital eccentricity and Roche lobe overflow at periastron.

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